AD-A046 155 ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND DOVER--ETC F/G 9/2

THE BOOK OF CLYDE WITH A TORQUE-ING CHAPTER.(U)

OCT 77 R I ISAKOWER, R E BARNAS

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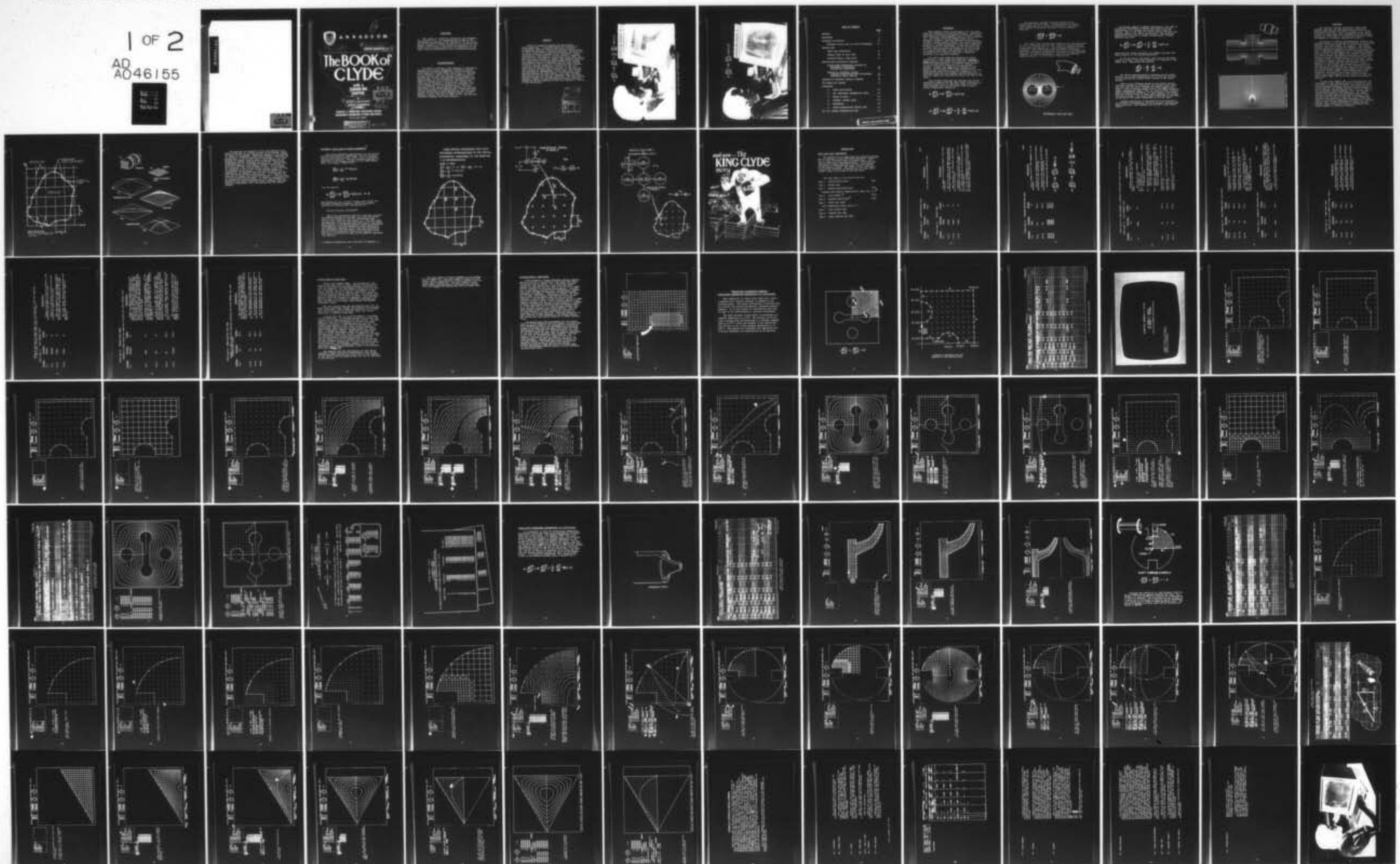

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USERS MANUAL 77 - 3

The BOOK of CLYDE

with a TORQUE-ING CHAPTER.

by

10 ROBERT I. ISAKOWER

ROBERT E. BARNAS

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NOV 4 1977

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12 175p.

SCIENTIFIC & ENGINEERING APPLICATIONS DIVISION

MANAGEMENT INFORMATION SYSTEMS DIRECTORATE

DOVER, NEW JERSEY

DISTRIBUTION STATEMENT A

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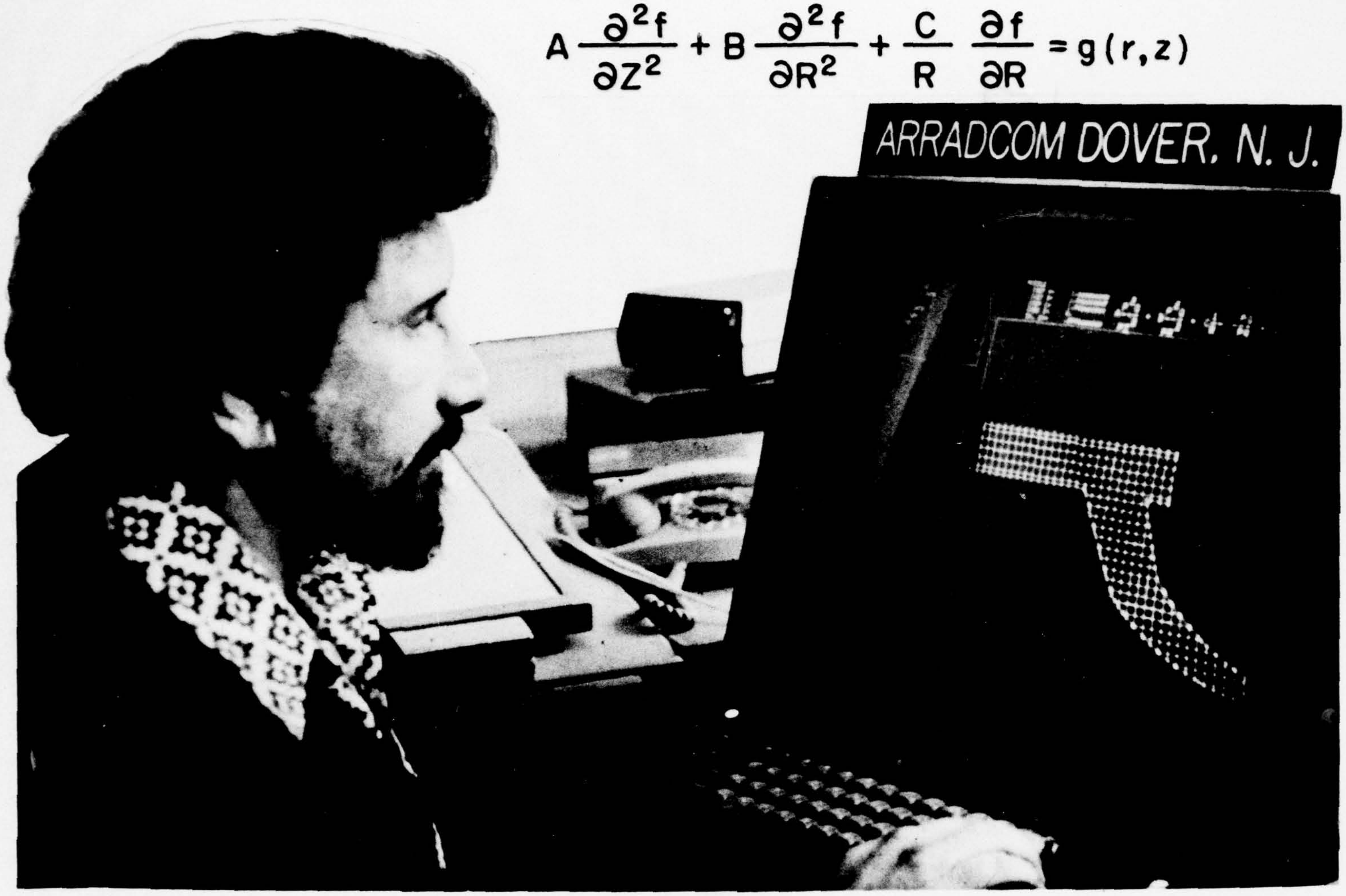
ACKNOWLEDGEMENTS

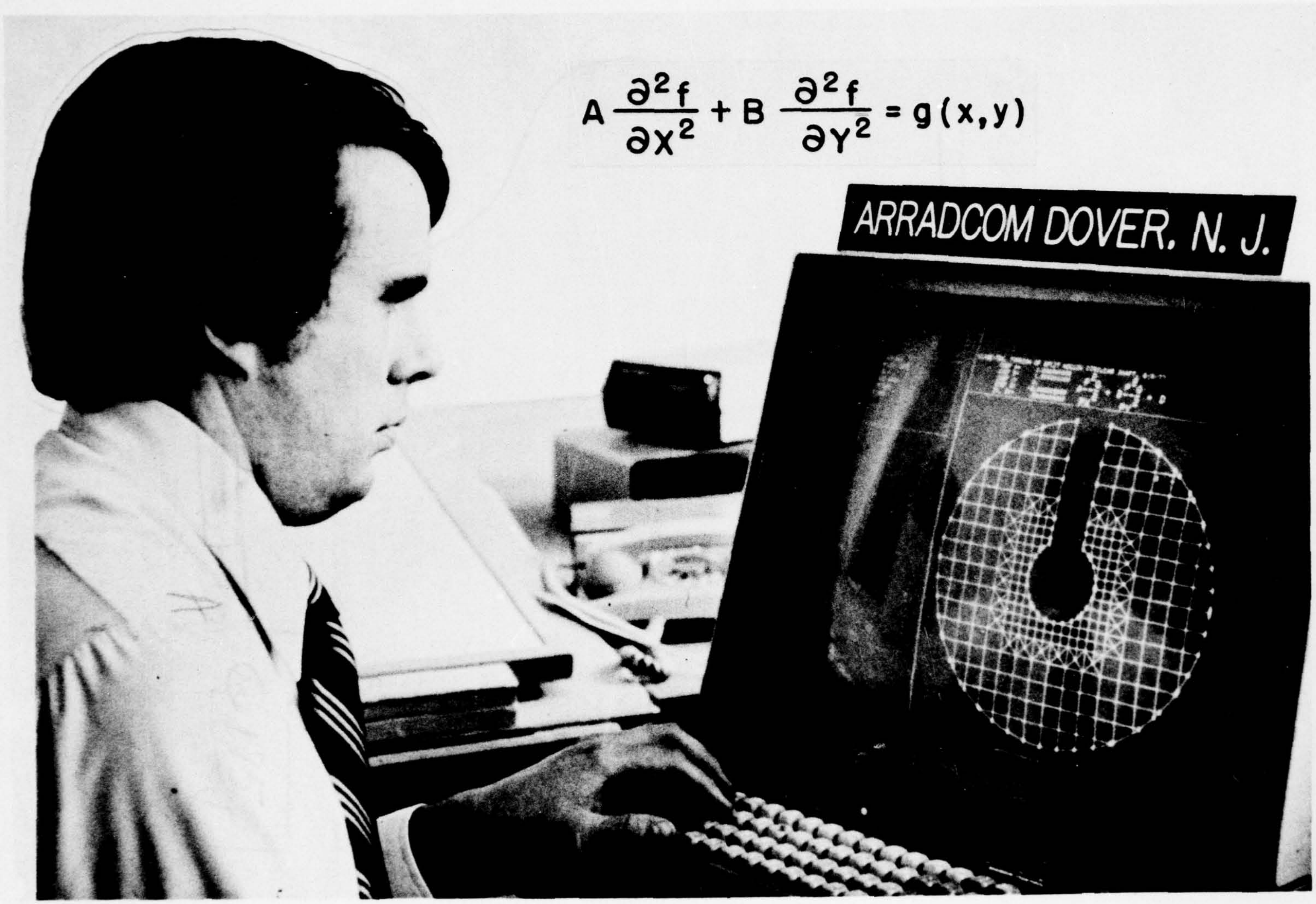
Mr. Robert E. Barnas of the Scientific & Engineering Applications Division, Management Information Systems Directorate was THE programmer for all the graphics and batch versions of CLYDE, while Chief Robert I. Isakower of the Division, after his initial conceptualization, provided the driving force throughout this project. Mr. Edward Lacher, of this Directorate, provided the linear equation solution routine while Mr. Ray Thorley and others of the Drafting & Illustrations Division, Technical Support Directorate created the outstanding artwork so necessary for a good publication. The perserverance of the authors affirms once more the correctness of the words of Sir Edmund Burke: " Those who carry on great works must be proof against the most fatiguing delays, the most mortifying disappointments, the most shocking insults, and what is worst of all, the most presumptuous judgement upon their designs".

ABSTRACT

CLYDE is a computer language for your differential equations. It provides numerical solutions to an important class of second order,elliptic partial differential equations (Laplace and Poisson) which appear in almost every branch of applied mechanics: governing the solutions to design problems in heat conduction, stress concentration, and potential fields (electric, magnetic, electrostatic, gravitation, irrotational fluid flow, etc..). There are three versions of CLYDE. This document describes the capabilities of the CDC 6000/TEKTRONIX 4014 storage tube graphics version (CLYDE-TEK) and the batch version (CLYDE-B) and also serves as a preliminary user's manual. An earlier version (CLYDE-274), written for the CDC 6500/1700/274 refresh graphics facility, is described in MISD Information Report 73-1, January 1973, and includes the extension of the solution to the fourth order stress analysis equation for flat plates. All CLYDE versions were written for CDC 6000 host computers under the SCOPE operating system with overlay structures. Two applications covered in detail in this document are steady state heat conduction and the membrane or soap film analogy of torsion of bars and shafts.



AUTHOR WITH NOZZLE HEAT TRANSFER PROBLEM



AUTHOR WITH SHAFT TORSION PROBLEM

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BACKGROUND

Most armament design is governed by the classical ideas and equations of continuum mechanics. Through the descriptive differential equations of elasticity, classical mechanics, electromagnetic theory, fluid mechanics, etc., the working state of armament items may be accurately studied. Physical phenomena in continuous systems - elastic bodies, fluids - are usually described by partial differential equations with their associated boundary or initial conditions. Closed form solutions to these PDE's are rarely available in the design room with its configurations that perversely do not conform to classical text book illustrations. Therefore, in the harsh world of reality, recourse to numerical solutions is an absolute necessity.

One widely used numerical technique is finite differences. CLYDE solves two dimensional boundary value problems with generalized contours, using finite difference approximations. A boundary value problem is one in which some function(s) of the problem variable is known, but only at the boundary of the problem. Steady state temperature distribution by means of heat conduction is a good example of this: the temperatures around the boundary or periphery of an arbitrary shape are kept constant and the problem is to find the temperature distribution within the area of the shape.

This document describes two versions (the latest interactive graphics and the basic batch versions) of a numerical solution to an important class of boundary value problems involving the second order elliptic partial differential equations:

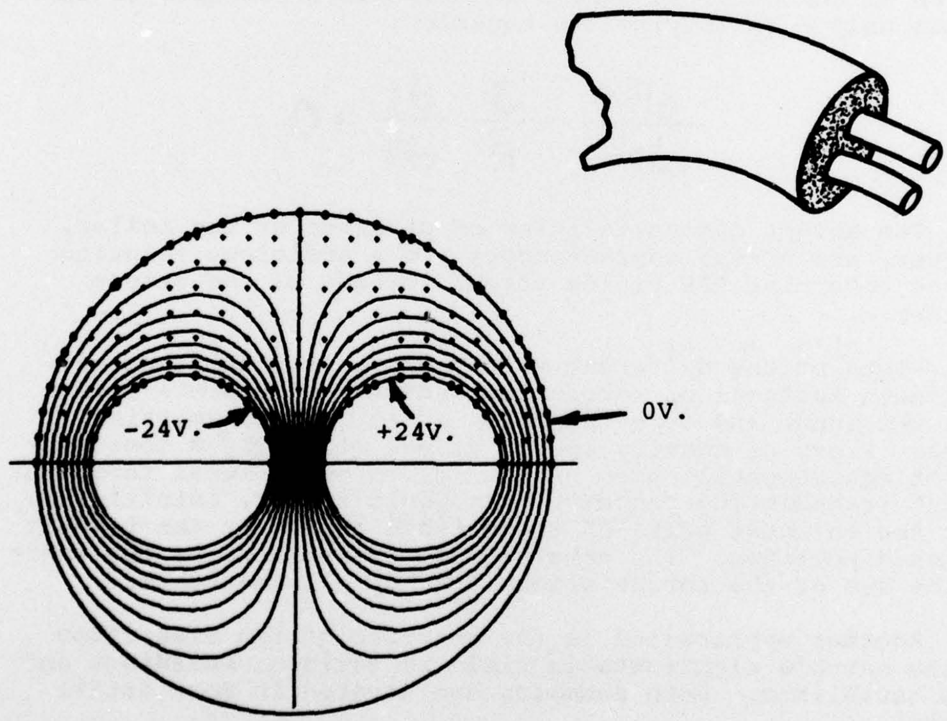
$$A \frac{\partial^2 f}{\partial X^2} + B \frac{\partial^2 f}{\partial Y^2} = g(x,y)$$

$$A \frac{\partial^2 f}{\partial Z^2} + B \frac{\partial^2 f}{\partial R^2} + \frac{C}{R} \frac{\partial f}{\partial R} = g(r,z)$$

To illustrate, consider the cross-section of an experimental twin-lead cable. The distribution of electrical potential (E, in volts) is described by the second order partial differential equation (called a harmonic equation):

$$\frac{\partial^2 E}{\partial X^2} + \frac{\partial^2 E}{\partial Y^2} = 0$$

The problem was run with the surface of one lead maintained at +24 V., the other lead at -24V., while the outer sheathing of the cable was kept at 0 V. The resulting computer solution generated a plot showing the lines of constant electrical potential. The finite difference grid nodes are displayed over only half the cable cross-section. Since the problem possessed symmetry, it was only necessary to work with the smallest repeating section - in this case, a semi-circle.



EXPERIMENTAL TWIN-LEAD CABLE

As another example of CLYDE's application, this time in cylindrical coordinates, consider the problem of stress concentration in a stepped and grooved shaft loaded in torsion. This is the case of a solid circular cylinder with varying diameter (the collar and grooves). The governing compatibility equation in terms of Saint-Venant's stress function f(R,Z) is:

$$A\frac{\partial^2 f}{\partial Z^2} + B\frac{\partial^2 f}{\partial R^2} + \frac{C}{R}\frac{\partial f}{\partial R} = g(r,z)$$

where g(r,z)=0 within the shaft (r,z domain) and some constant value(s) on the various boundaries.

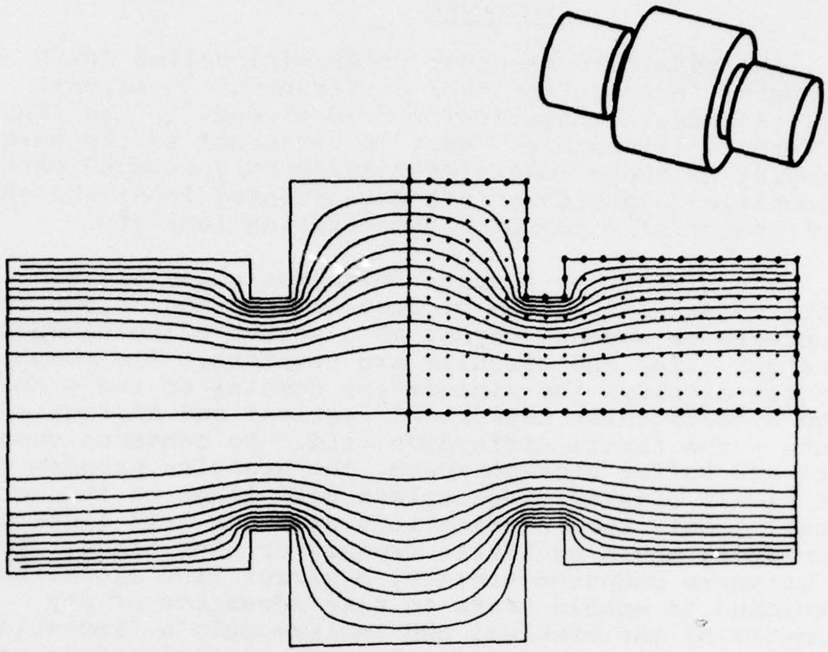
At the far ends of the shaft, away from the discontinuities of contour, the stress function is a function of the radius only - satisfying the equation:

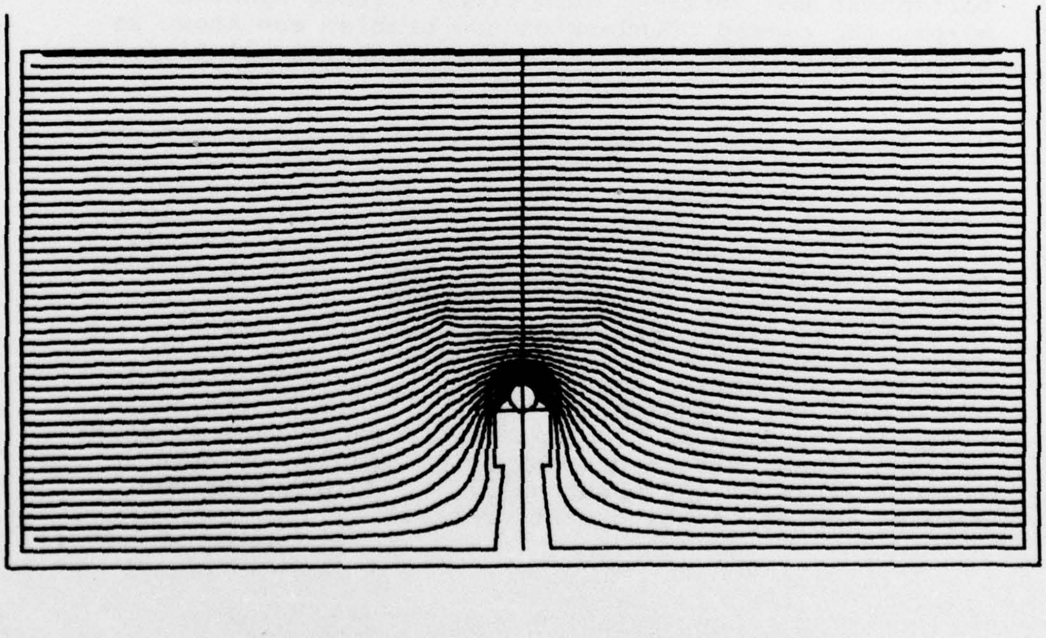
$$\frac{d^2 f}{dR^2} - \frac{3}{R}\frac{df}{dR} = 0$$

The abrupt discontinuities of diameter at the collar, however, are stress concentrators and a judicious solution of the governing PDE yields visual insight of the stress pattern.

Plots of the different values of the stress function represent surfaces of revolution, and adjacent plots represent the inner and outer surfaces of torque transmitting tubes. Plots of equally spaced values of f ($\Delta f =$ constant) depict equimomental tubes - that is, tubes of equal torque or moment transmitting capacity. It would appear, intuitively, that the thinnest parts of these tubes represent the highest stressed portions. The total torque transmitted by the shaft is the sum of the torque transmitted by all the tubes.

Another application is the charting of the distortion of the earth's electrostatic field by terrain, buildings and even earthlings. Both examples are covered in more detail later.





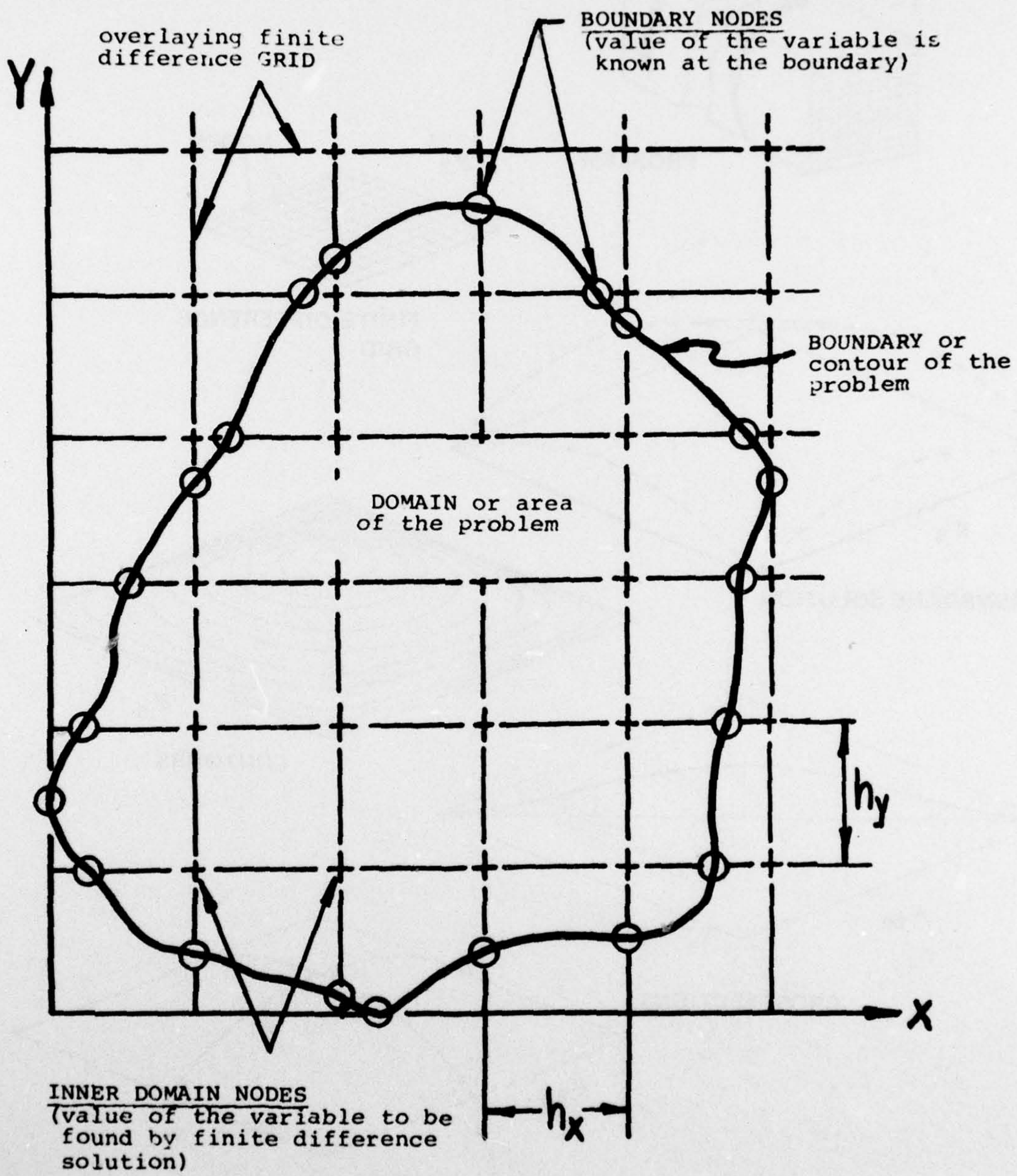
CLYDE-TEK, EARTHS ELECTROSTATIC FIELD #1

PROCEDURE

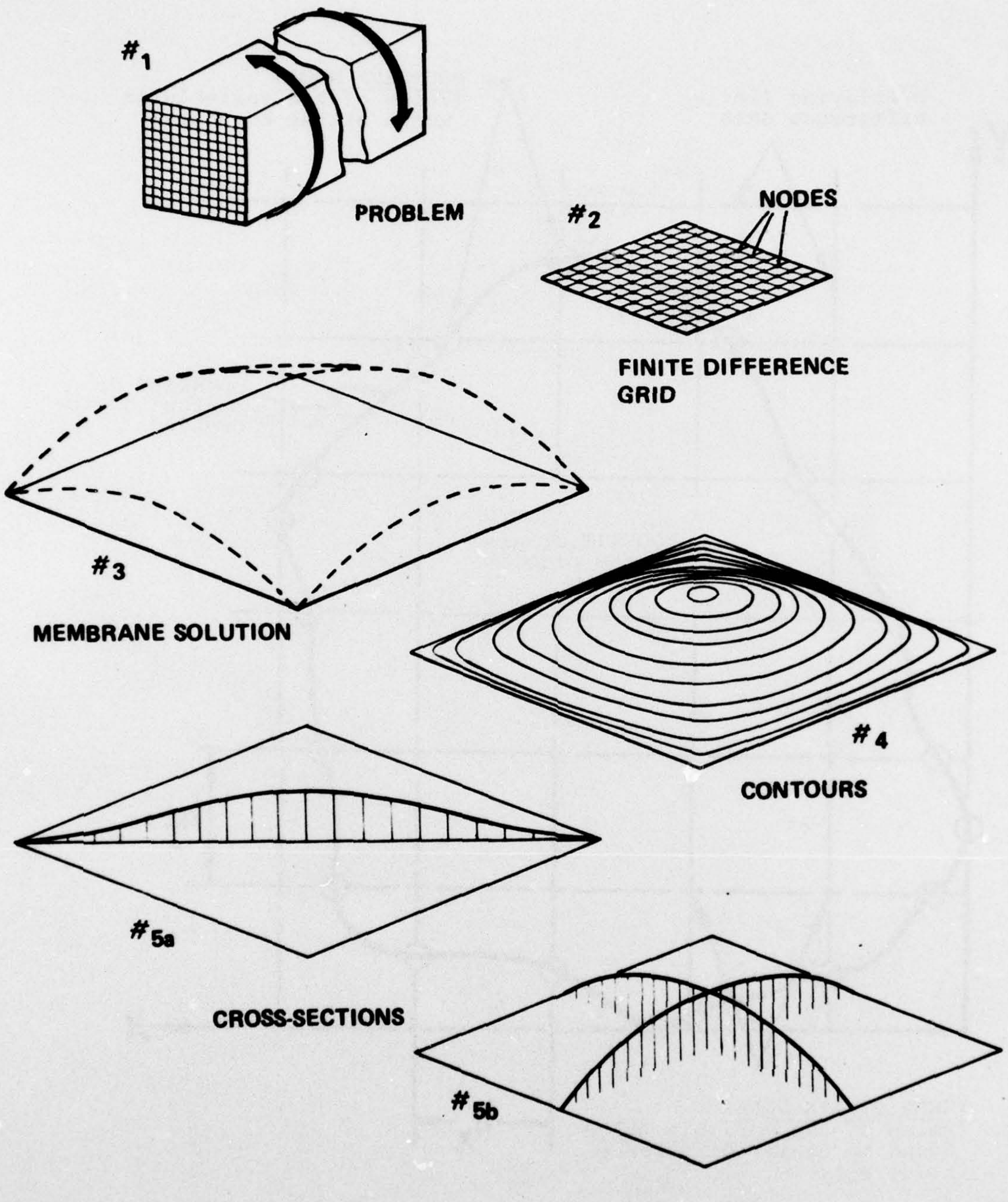
The resulting computer program(s) called CLYDE (Computer Language for Your Differential Equations) employs those mathematical models already in the finite difference literature. What is different is the unique blending of these models with ARRADCOM developed pattern recognition algorithms in a man-oriented input and output environment of a computer time-sharing facility.

The picture or contour (mathematically speaking, the enclosed domain) of the problem is inputted to the program, generally on punched cards, as a series of contiguous straight lines and circular arc segments. The computer program overlays the picture (or domain) of the problem with a rectangular network of vertical and horizontal grid lines - the finite difference grid. To conserve computer core and buffer storage space, the graphics program does not always display the complete grid lines on the screen. Usually, only the intersections of these grid lines are displayed, shown as little crosses or plus signs. Again, to conserve computer storage, a mirror line algorithm was developed to enable users to take advantage of any symmetry of the problem, and analyze only a "repeating section" of the problem domain. The intersections of the horizontal and vertical grid lines with the boundary are called boundary nodes and are shown in the graphics version as little circles. The intersections of the horizontal and vertical grid lines (little crosses) within the closed boundary of the problem are known as inner domain nodes, and it is here that the solution is desired.

At each inner domain node, a finite difference approximation to the governing partial differential equation (PDE) is generated by CLYDE. The resulting set of linear algebraic equations are solved simultaneously by the program for the unknown problem variable (temperature, voltage, stress function, etc..) at each node in the overlaying finite difference grid. The graphics version also generates, and displays on the screen, iso-value contour maps for any desired values of the variable just solved for. This way, a more meaningful picture of the solution is made available to the engineer; in the form of temperature distributions, constant voltage lines, stress concentration graphs, or even contour lines of different values of deformation and bending moment in structural problems.



overlaying finite difference GRID
BOUNDARY NODES
(value of the variable is known at the boundary)
Y
BOUNDARY or contour of the problem
DOMAIN or area of the problem
h_y
X
INNER DOMAIN NODES
(value of the variable to be found by finite difference solution)
h_x


#1
PROBLEM
#2
NODES
FINITE DIFFERENCE GRID
#3
MEMBRANE SOLUTION
#4
CONTOURS
#5a
CROSS-SECTIONS
#5b

The user may also specify a finer grid spacing to increase resolution in critical regions of the problem, modify the scale of the display, change the boundary of the problem (or redraw it completely), and change boundary conditions and coefficients --- all at the face of the screen. It is also possible to request CLYDE to pass a plane through the two dimensional picture displayed on the screen. This plane is perpendicular to the screen and shows as a straight line. CLYDE will generate a new display showing a cross section (or elevation) view from the edge or side. In this manner the variation or plot of the solved variable along that line is displayed on the screen. If the problem geometry is symmetrical, the designer does not have to display and work with the entire picture of the problem. If he desires, he need only to display the "repeating section". (This is done in the illustrative solutions). In essence, the graphics user may examine the problem solution at will, and redesign the problem at the screen (problem contour, boundary conditions, equation coefficients, etc.) and resolve the "new design" problem.

ENGINEERS' QUICK LOOK AT FINITE DIFFERENCES *

The finite difference approximations to the partial differential operators, substituted into the governing partial differential equation (PDE), yield an algebraic approximation equation. One such algebraic equation is generated by the computer program at each INNER DOMAIN NODE. For example, substituting

$$\frac{\partial^2 f}{\partial x^2} = \frac{1}{h_x^2}(f_1 - 2f_0 + f_3)$$

$$\frac{\partial^2 f}{\partial y^2} = \frac{1}{h_y^2}(f_2 - 2f_0 + f_4)$$

into the equation

$$A\frac{\partial^2 f}{\partial x^2} + B\frac{\partial^2 f}{\partial y^2} = g(x,y) \equiv D$$

and letting $h_x = h_y = h$ (for a square grid) yields the following algebraic expression called the harmonic operator at a typical node (labeled node 0):

$$A(f_1+f_3)+B(f_2+f_4)-(A+B)2f_0=h^2D$$

This finite difference equation at node zero involves the unknown variable at node zero (f_0) plus the unknown value of the variable at the four surrounding nodes (f_1,f_2,f_3,f_4), plus the grid spacing (h). The five nodes involved form a four arm star with node zero at the center. This algebraic or difference equation could be conveniently visualized as a four arm computation stencil made up of five "balloons" connected in this four arm star pattern and overlayed on the grid nodes. The value within each balloon is the coefficient by which the variable (f) at that node is multiplied to make up the algebraic approximation equation.

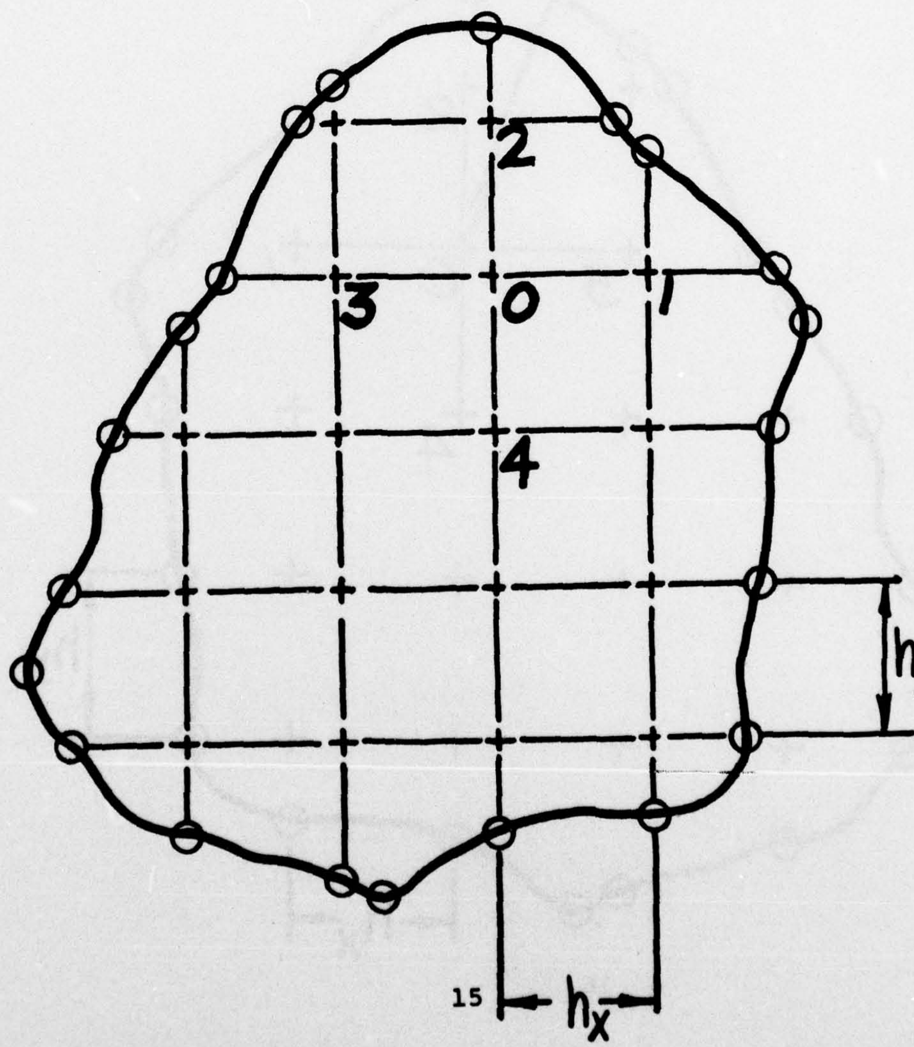
* (Complete mathematical why's and how's in Appendix B)

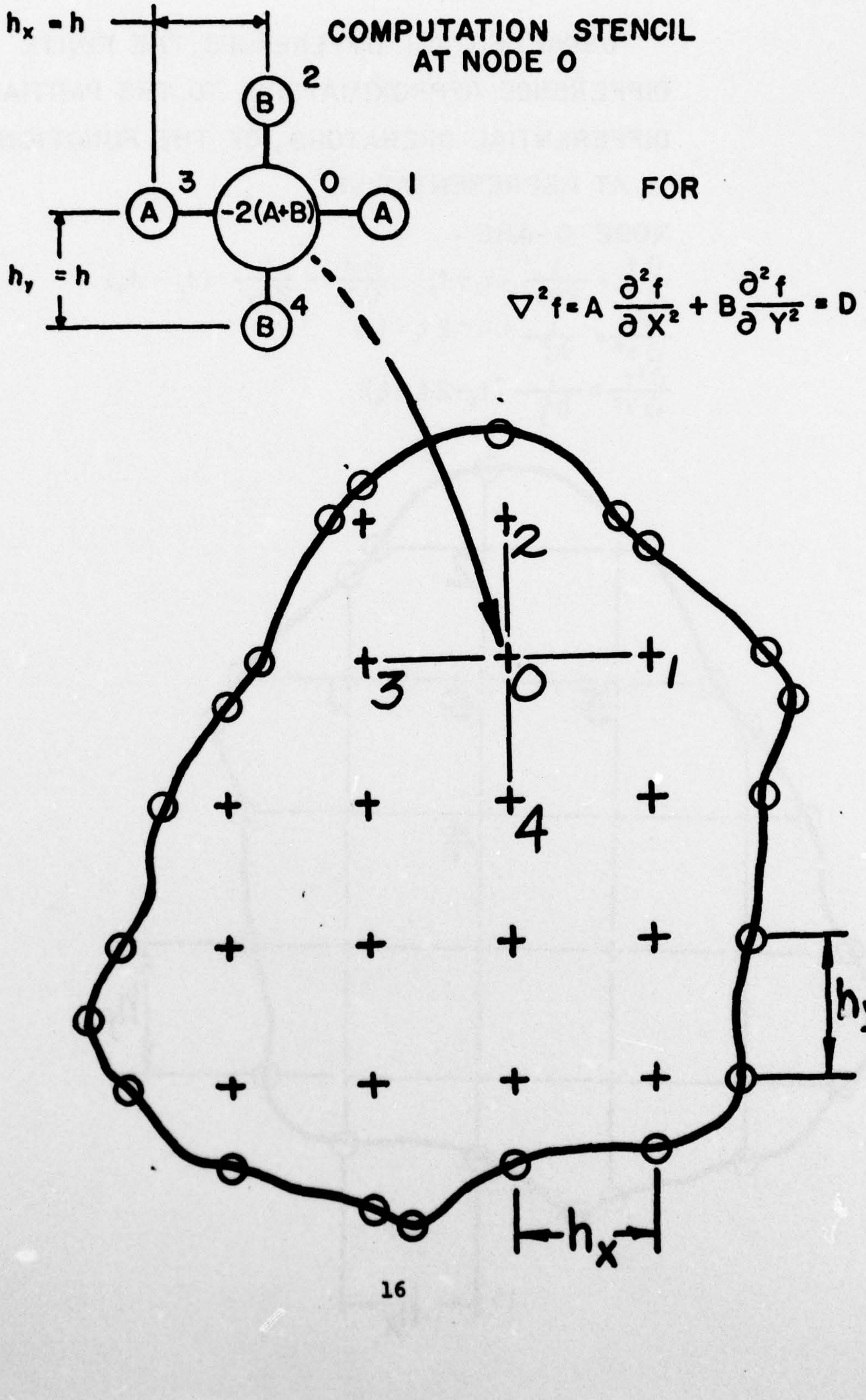
USING CENTRAL DIFFERENCES, THE FINITE DIFFERENCE APPROXIMATIONS TO THE PARTIAL DIFFERENTIAL OPERATORS, OF THE FUNCTION f, AT REPRESENTATIVE NODE 0 ARE:

$$\frac{\partial f}{\partial x} = \frac{1}{2h_x}(f_1 - f_3), \quad \frac{\partial f}{\partial y} = \frac{1}{2h_y}(f_2 - f_4)$$

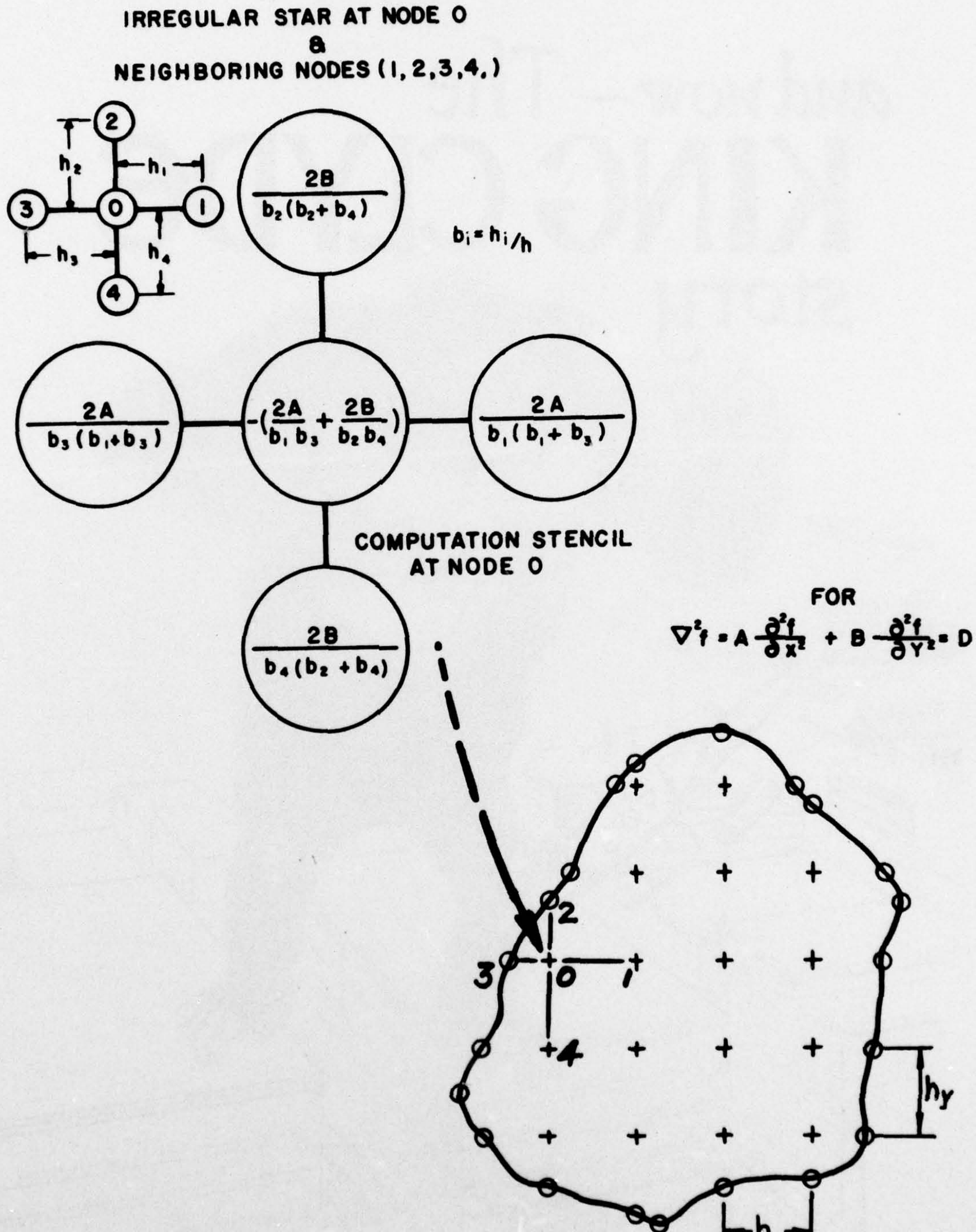
$$\frac{\partial^2 f}{\partial x^2} = \frac{1}{h_x^2}(f_1 - 2f_0 + f_3)$$

$$\frac{\partial^2 f}{\partial y^2} = \frac{1}{h_y^2}(f_2 - 2f_0 + f_4)$$

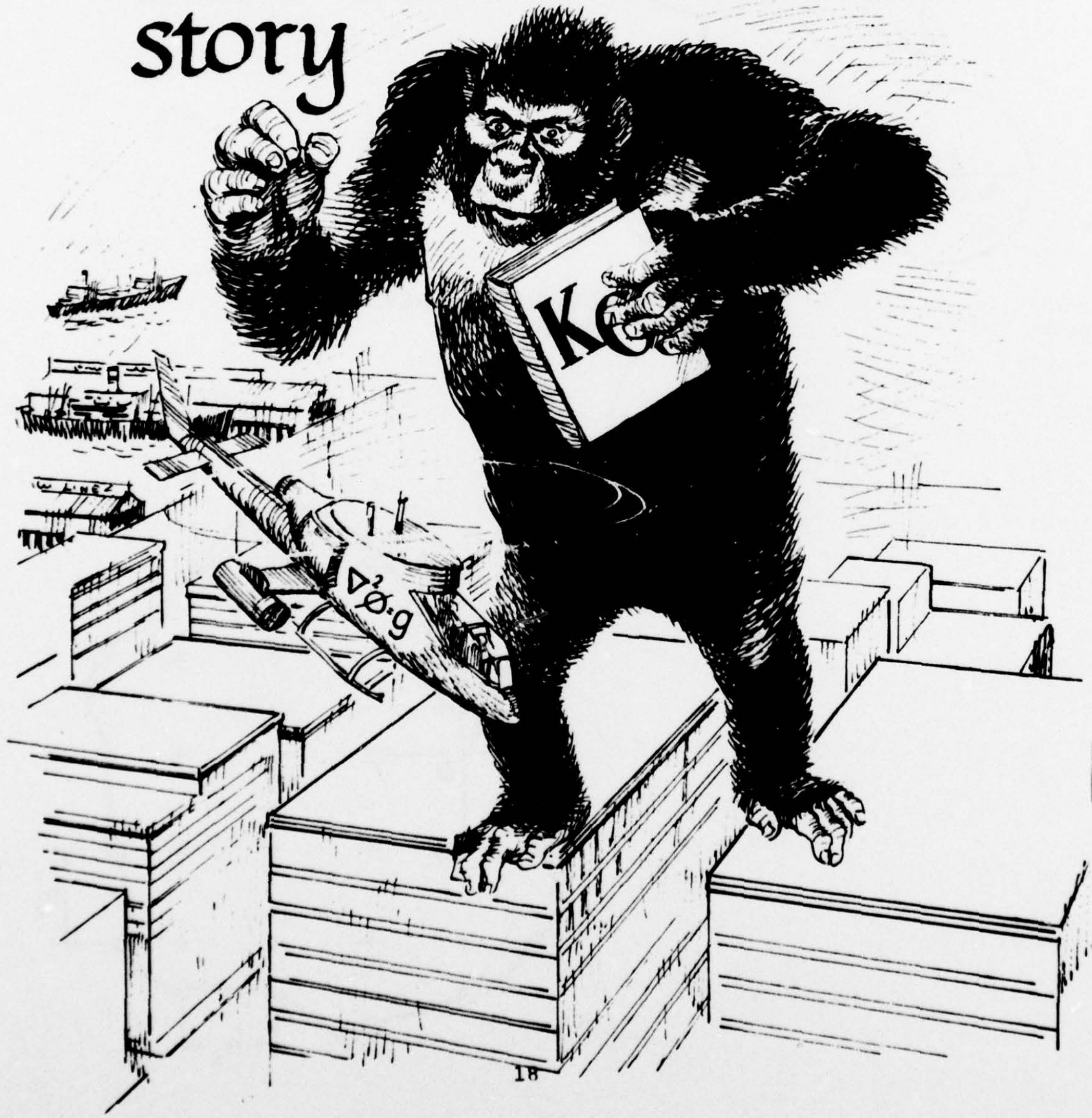




COMPUTATION STENCIL
AT NODE O
FOR
$\nabla^2 f = A \frac{\partial^2 f}{\partial X^2} + B \frac{\partial^2 f}{\partial Y^2} = D$
$h_x = h$
$h_y = h$
-2(A+B)
A
B
0
1
2
3
4
h_y
h_x


IRREGULAR STAR AT NODE O
&
NEIGHBORING NODES (1, 2, 3, 4,)
h_1 h_2 h_3 h_4
$\frac{2B}{b_2(b_2+b_4)}$
$b_i = h_i/h$
$\frac{2A}{b_3(b_1+b_3)}$
$-\left(\frac{2A}{b_1 b_3}+\frac{2B}{b_2 b_4}\right)$
$\frac{2A}{b_1(b_1+b_3)}$
COMPUTATION STENCIL
AT NODE O
$\frac{2B}{b_4(b_2+b_4)}$
FOR
$\nabla^2 f = A\frac{\partial^2 f}{\partial X^2} + B\frac{\partial^2 f}{\partial Y^2} = D$
h_y
h_x

and now — The KING CLYDE story



PROGRAM DATA

INPUT DATA CARD PREPARATION

The complete set of input data and production options must be inputted to the CLYDE-BATCH program on a deck of (up to nine) different types of punched cards. Only four of these nine types are required to initialize the interactive graphics CLYDE-TEK version, since problem customizing is performed and output options selected at the graphics screen. The subset of four card types required for CLYDE-TEK initialization are noted with a "(TEK)" typed to the right of the card type.

The nine types of input data cards are:

Type 1	IDENTIFICATION CARD	(TEK)
Type 2	OPTION CARD	
Type 3	PROBLEM DEFINITION CARD	(TEK)
CONTOUR LINE SEGMENT IDENTIFICATION CARD, sets of 2*		
Type 4	LINE SEGMENT *	(TEK)
Type 5	BOUNDARY CONDITIONS *	(TEK)
Type 6	FINER GRID CARDS	
PLOT INSTRUCTION CARDS, sets of 3		
Type 7	PLOT CONTROL CARD	
Type 8	CONTOUR PLOT CARD	
Type 9	CROSS SECTION PLOT CARD	

(Card Type 1) IDENTIFICATION CARD (TEK)

Columns	Variable	Format	Explanation
1-80	IDENT	8A10	Any identifying alphanumeric text.

(Card Type 2) OPTION CARD

Columns	Variable	Format	Explanation
1-5	IMESH	I5	The number of rectangles where a fine grid is desired.
6-10	NPLOT	I5	The total number of CALCOMP plots desired (*contours, cross-sections, and combinations*).
11-15	IPRNT	I5	When non-zero, the individual node output will not be printed.
16-20	ITEKF	I5	TEKTRONIX output display control: If 0, no information is written to file REBEL. If 1, PLOT information is written to file REBEL for CALCOMP plots. If -1, Plot information is written to file REBEL for use by the TEKTRONIX display program viewer. No CALCOMP plots are generated.

(Card type 3) PROBLEM DEFINITION CARD (TEK)

Columns	Variable	Format	Explanation
1-5	NCPT	I5	Total number of all line segments in all contours.
6-15	DX	F10.0	Spacing of the overlaying finite difference grid in the x-direction.
16-25	DY	F10.0	Spacing of the overlaying finite difference grid in the y-direction.
26-35 36-45 46-55 56-65	COEFA COEFB COEFC COEFD	F10.0 F10.0 F10.0 F10.0	Coefficients of the PDE to be solved:

$$A \frac{\partial^2 f}{\partial X^2} + B \frac{\partial^2 f}{\partial Y^2} = D(x,y)$$

$$A \frac{\partial^2 f}{\partial Z^2} + B \frac{\partial^2 f}{\partial R^2} + \frac{C}{R} \frac{\partial f}{\partial R} = D(r,z)$$

(NCPT pairs of LINE SEGMENT & BOUNDARY CONDITIONS cards are required)

(Card type 4) LINE SEGMENT CARD (TEK)

Columns	Variable	Format	Explanation
1-2	KC	I5	Sequence numbers of the line segment. This is to help the user keep the cards in order.
4-5	WHAT	A2	The type of line segment: SL = straight line CA = circular arc ML = mirror line (a line of symmetry - always a straight line) EL = equation line (permitting a linear variation in boundary values from one end of the line segment to the other) EA = equation arc (permitting a linear variation in boundary values from one end of the arc segment to the other)
6-15	X1	F10.0	X-coordinate of first point on the line segment or arc.
16-25	Y1	F10.0	Y-coordinate of first point on the line segment or arc.
26-35	X2	F10.0	X-coordinate of the last point on the line segment or arc.

(Card type 4) LINE SEGMENT CARD (continued)

Columns	Variable	Format	Explanation
36-45	Y2	F10.0	Y-coordinate of the last point on the line segment or arc.
46-55	X0	F10.0	X-coordinate of origin of circular arc - ignored if WHAT is SL, ML, or EL.
56- 65	Y0	F10.0	Y-coordinate of origin of circular arc - ignored if WHAT is SL, ML, or EL.
68-70	DIR	F3.0	Direction of "development" of circular arc, from first point to last point: CCW = Go counterclockwise CW = Go clockwise. Ignored if WHAT = SL, ML, or EL.

(Card type 5) BOUNDARY CONDITIONS CARD (TEK)

Columns	Variable	Format	Explanation
1-10	XINISH	F10.3	Boundary condition (value of problem variable) along entire line segment. When WHAT=EL or EA, XINISH should be the value of the variable at the last (X2,Y2) point of the line segment.
11-20	XVAL	F10.3	Value of the problem variable at the first (X1,Y1) point of the line segment.

(Card type 6) FINER GRID CARD

(There are to be IMESH of these cards)

Columns	Variable	Format	Explanation
1-15	XC1	E15.7	The minimum X coordinate of the rectangle defining the finer mesh region.
16-30	YC1	E15.7	The minimum Y coordinate of the rectangle defining the finer mesh region.
31-45	XC2	E15.7	The maximum X coordinate of the rectangle defining the finer mesh region.
46-60	YC2	E15.7	The maximum Y coordinate of the rectangle defining the finer mesh region.

(NPLOT of the sets of card types 7,8,9 are required. Each set requires a card type 7 plus either card types 8 or 9 or both)

(Card type 7) PLOT CONTROL CARD

Columns	Variable	Format	Explanation
1-5	MRANGE	I5	Number of groups or sets of contours to be calculated and drawn on this plot.
6-10	NCROSS	I5	Number of cross-section curves to be calculated and drawn on this plot.
11-15	IMIRR	I5	When the boundary of the problem includes mirror lines (ML), and IMIRR is zero, the full picture of the problem will be drawn.
16-20	INODE	I5	The inner domain nodes of the problem will not be drawn on the plot when INODE is non-zero.

(Card type 8) CONTOUR PLOT CARDS

(MRANGE of these cards are required following the PLOT CONTROL card).

Columns	Variable	Format	Explanation
1-5	NVALUES	I5	Number of equally spaced contours to be plotted. The contours are closed curves, depicting the location of a different value of the solved for problems variable. They are iso-value lines. By equally spaced contours, it is meant that the incremented value of the problem variable between successive contours is the same.
6-10	INEX	I5	Inclusive or exclusive parameter: If the contour plots of equally spaced values of variable are to include those of the minimum and maximum values, INEX must be 1. Otherwise, set INEX to 0.
11-15	ICU	I5	If set to 1, the user is to specify the starting or minimum value for contour plots and the incremental value for all the contours to be plotted (NVALUES contours to be plotted). Needless to say, ICU must override INEX.
16-25	DV	F10.5	The increment value, between successive contour value plots. Specified by user, if ICU is 1.
26-35	XSTART	F10.5	The value at which contour plotting should begin. Specified by user, if ICU is 1. If XSTART is less than the minimum solved for value, it is set to the minimum value.

(Card type 9) CROSS-SECTION PLOT CARD

(NCROSS of these cards are required following the PLOT CONTROL and (any) CONTOUR PLOT cards)

Columns	Variable	Format	Explanation
1-15	XA	E15.7	The X-coordinate of the first end point of the line representing the plane cutting the contour lines. The cross-section is a profile view of the problem variable gradient along the cutting plane.
16-30	YA	E15.7	The Y-coordinate of the first end point of the line representing the cutting plane.
31-45	XB	E15.7	The X-coordinate of the other end point of the line representing the cutting plane.
46-60	YB	E15.7	The Y-coordinate of the other end point of the line representing the cutting line.

GENERAL NOTES ON INPUT DATA

CONTOUR LINE SEGMENT CARDS - The boundaries of the problem (the outer and all inner contours) are inputted to CLYDE as polystrings of contiguous straight lines and circular arc segments. The line segment sequence for any contour or boundary may begin with any line segment of that contour and may proceed in either a clockwise or counterclockwise direction around that boundary. Once begun, however, the segments must be input in order, in the direction started, until that boundary is completed. Each LINE SEGMENT card must be followed by a BOUNDARY CONDITIONS card. There are NCPT pairs of these (LINE SEGMENT and BOUNDARY CONDITIONS) cards.

Only the circular arcs (CA) and equation arcs (EA) require origin coordinate (XO,YO) and direction of development (DIR) input data. These fields are ignored by the program when the line segments are straight lines (SL), mirror lines (ML), or equation lines (EL).

A *mirror line* (ML) is a line of symmetry, a veritable line of reflection. Its primary function is to permit the analysis of a "repeating section" of the problem. The same number of grid lines overlaying this smaller, but representative, portion as is normally used over the entire problem area produces a finer finite difference net. This yields higher resolution and a more accurate numerical approximation while requiring no more storage or running time - a delightful freebie. Unfortunately, the present state of CLYDE's development allows for horizontal and vertical mirror lines only, so that a quadrant is the smallest symmetrical portion that can be presently handled. The user is cautioned to position his problem so that any vertical mirror line is the leftmost line in the data set and any horizontal mirror line the lowest horizontal line in the data set. Incidentally, a mirror line also implies (and may be so used) a boundary condition of the first derivative of the problem variable, normal to the boundary, being zero. $\partial\phi/\partial n = 0$

The equation line (EL) and equation arc (EA) merely indicate a linear variation in the boundary value of the problem variable from one end of the line (or arc) segment to the other, along the length of the line (EL) or the curve of the arc (EA).

The total number of contour segments in any problem may not exceed 125. The total number of inner and outer contour nodes (intersections of contour segments and grid lines) may not exceed 500. The total number of inner domain nodes (intersections of horizontal and vertical grid lines <u>within</u> the problem area) may not exceed 1000.

SOLUTION MATRIX & BAND WIDTH

CLYDE generates a finite difference equation approximation to the PDE to be solved at each inner node within the problem area or domain. For a relatively straight forward ten unit square with a unit grid this would produce 81 equations (one for each of the 9x9 or 81 nodes) with 81 unknowns, to be solved simultaneously. Considering a large complex problem, with a realistically (useful) fine grid, the number of equations and unknowns becomes horrendously formidable. Realizing, however, that there are, at most, five non-zero coefficients in any of the equations it was decided to keep the non-zero terms clustered "tightly" about the main diagonal and use a linear equation solution routine. This routine provides a "neat" computer procedure for solving our anticipated N X N system of linear simultaneous equations whose coefficient matrix is of the band form (i.e., it has non-zero elements only about the main diagonal and zeroes elsewhere). Only the band elements need be stored, permitting the solution of large systems of linear simultaneous equations in relatively few storage locations. Gaussian elimination is used, modified to take advantage of the reduced matrix. The routine also uses partial pivoting to reduce roundoff error.

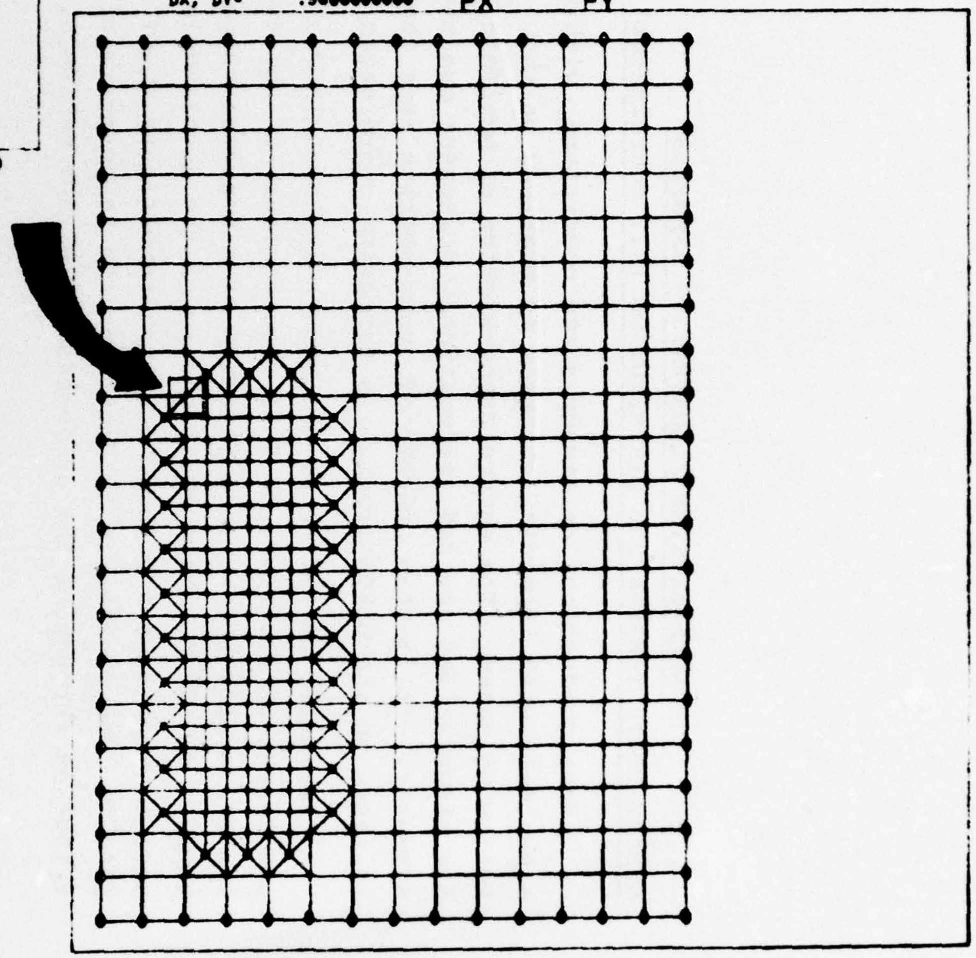
The maximum band width programmed into the present CLYDE is 90 and exceeding this will produce a program stop and a message as shown on the accompanying illustration. A box is displayed about the node whose total bandwidth exceeds 90 or about the node whose "left hand" or "right hand bandwidth" exceeds 45. The band width at any node is the total number of nodes from its neighbor immediately to its left to its immediate right neighbor. The node count is up the vertical grid lines from the left neighbor, through the node in question, and up to the right neighbor. Boundary nodes are not neighbors, nor are they counted. The CLYDE user should be carefully selective in his choice of initial grid spacing, problem orientation, shape and size of the finer mesh if any, and repeating section options to avoid exceeding the band width limit.

(C)-CONTINUE
(M)-MODIFY DATA
(P)-PLOT
(N)-NEW DATA
(R)-RETURN
(E-S)END

BAND WIDTH FOR MATRIX LARGER THEN 90

COEF A= 1.000000000
COEF B= 1.000000000
COEF C= 0.
COEF D= -2.000000000
DX, DY= .5000000000

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$

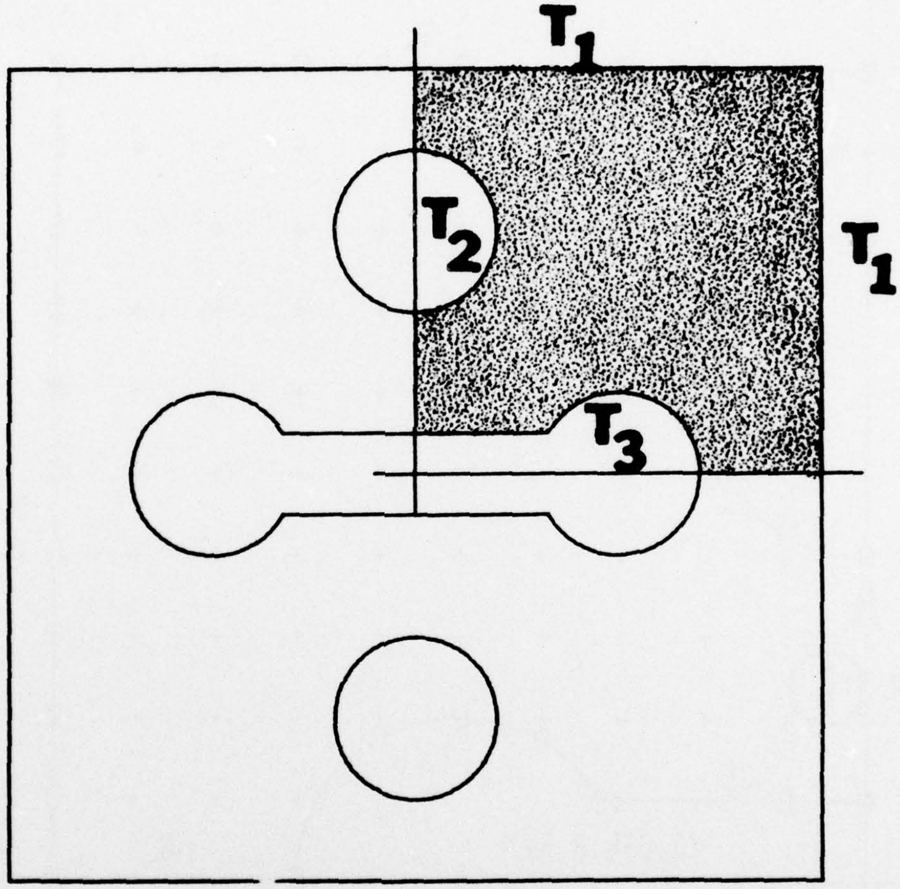


STEP-BY-STEP ILLUSTRATIVE EXAMPLES

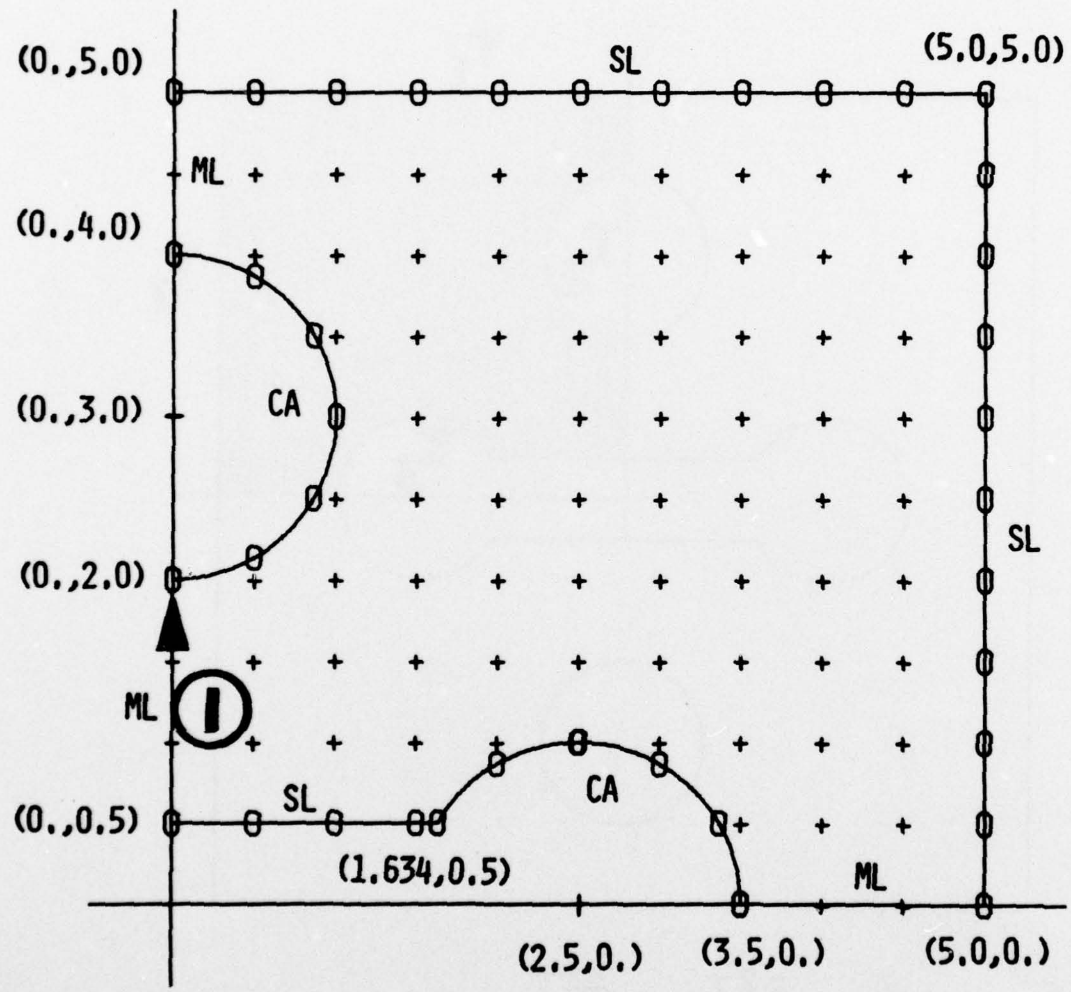
STEADY-STATE TEMPERATURE DISTRIBUTION (X,Y coordinates)

Heat conduction, at steady state conditions, within a manifold with irregular channels is examined on the following pages. The square cross-section of manifold with its circular and slotted perforations, possesses quadrant symmetry. It is this quarter of cross-section area that is input to the CLYDE program in cartesian coordinates.

The outer perimeter of the square is maintained at a constant temperature T_1 of 0° F. The contours of the two inner circular holes are maintained at a constant temperature T_2 of 50° F, while the boundary of the double-hole-slot is kept at yet a third constant temperature T_3 of 100° F. The problem is to determine the temperature distribution throughout the cross-section of the manifold.



$$\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} = 0$$



SOLUTION IS REQUIRED OVER ONE QUADRANT OF THE MANIFOLD ONLY.

IBM

FORTRAN Coding Form

GX28-7327-6 U/M 050**
Printed in U.S.A.

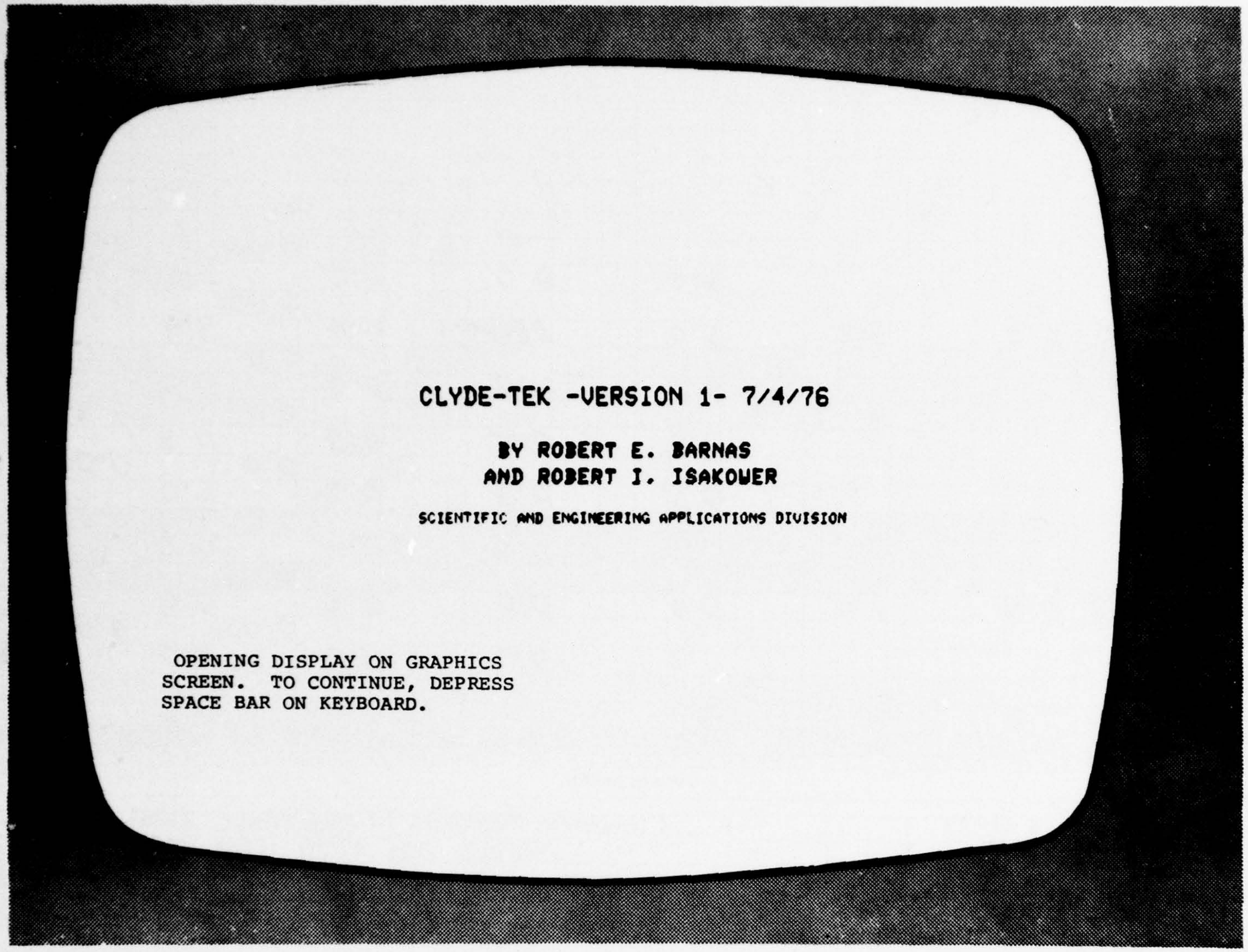
PROGRAM	PUNCH CARD INPUT DATA FOR STEADY/	PUNCHING INSTRUCTIONS	GRAPHIC		PAGE OF
PROGRAMMER	STATE HEAT TRANSFER IN SQUARE MANIFOLD		PUNCH		CARD ELECTRO NUMBER*

```
C  STATEMENT NUMBER | CONT | FORTRAN STATEMENT                                              | IDENTIFICATION SEQUENCE
HEAT CONDUCTION IN QUADRANT OF SQUARE MANIFOLD, CLYDE-TEK, 2/2/77
    8       0.5       0.5       1.0       1.0       0.0       0.0
  1 ML      0.0       0.5       0.0       2.0
     100.0     100.0
  2 CA      0.0       2.0       0.0       4.0       0.0       3.0  CCW
      50.0      50.0
  3 ML      0.0       4.0       0.0       5.0
      50.0      50.0
  4 SL      0.0       5.0       5.0       5.0
       0.0       0.0
  5 SL      5.0       5.0       5.0       0.0
       0.0       0.0
  6 ML      5.0       0.0       3.5       0.0
       0.0       0.0
  7 CA      3.5       0.0   1.63397       0.5       2.5       0.0  CCW
     100.0     100.0
  8 SL  1.63397       0.5       0.0       0.5
     100.0     100.0
```

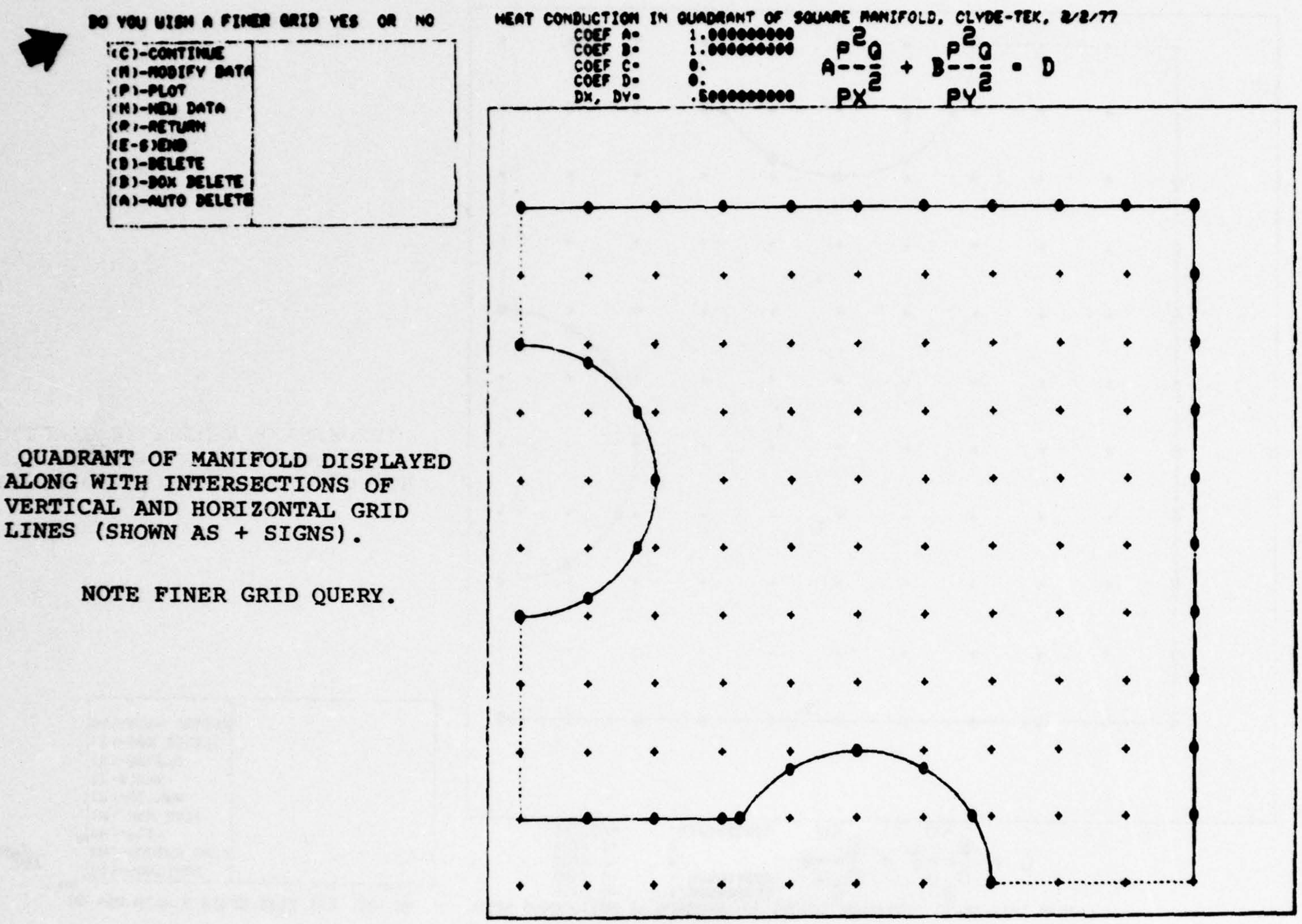
*A standard card form, IBM electro 888157, is available for punching statements from this form

**Number of forms per pad may vary slightly

PUNCH CARD INPUT FOR CLYDE-TEK.



OPENING DISPLAY ON GRAPHICS
SCREEN. TO CONTINUE, DEPRESS
SPACE BAR ON KEYBOARD.



QUADRANT OF MANIFOLD DISPLAYED ALONG WITH INTERSECTIONS OF VERTICAL AND HORIZONTAL GRID LINES (SHOWN AS + SIGNS).

NOTE FINER GRID QUERY.

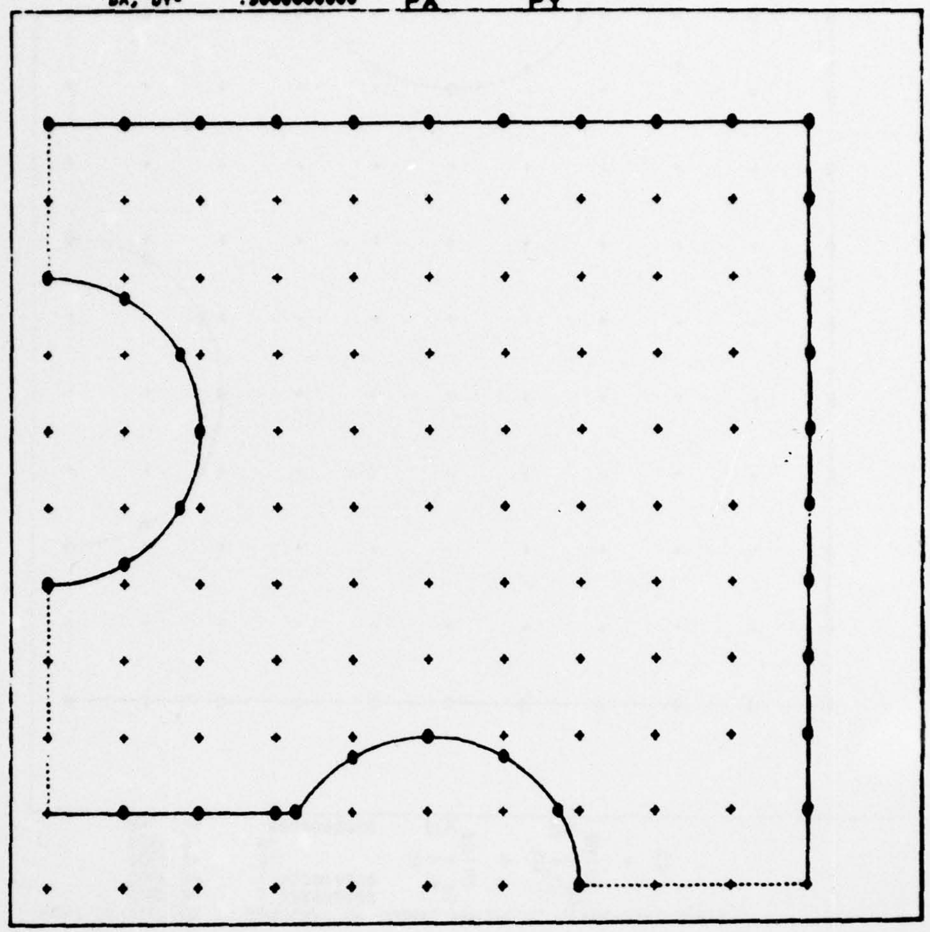
DO YOU WISH A FINER GRID YES OR NO
NO

(C)-CONTINUE
(M)-MODIFY DATA
(P)-PLOT
(N)-NEW DATA
(R)-RETURN
(E-S)END
(D)-DELETE
(B)-BOX DELETE
(A)-AUTO DELETE

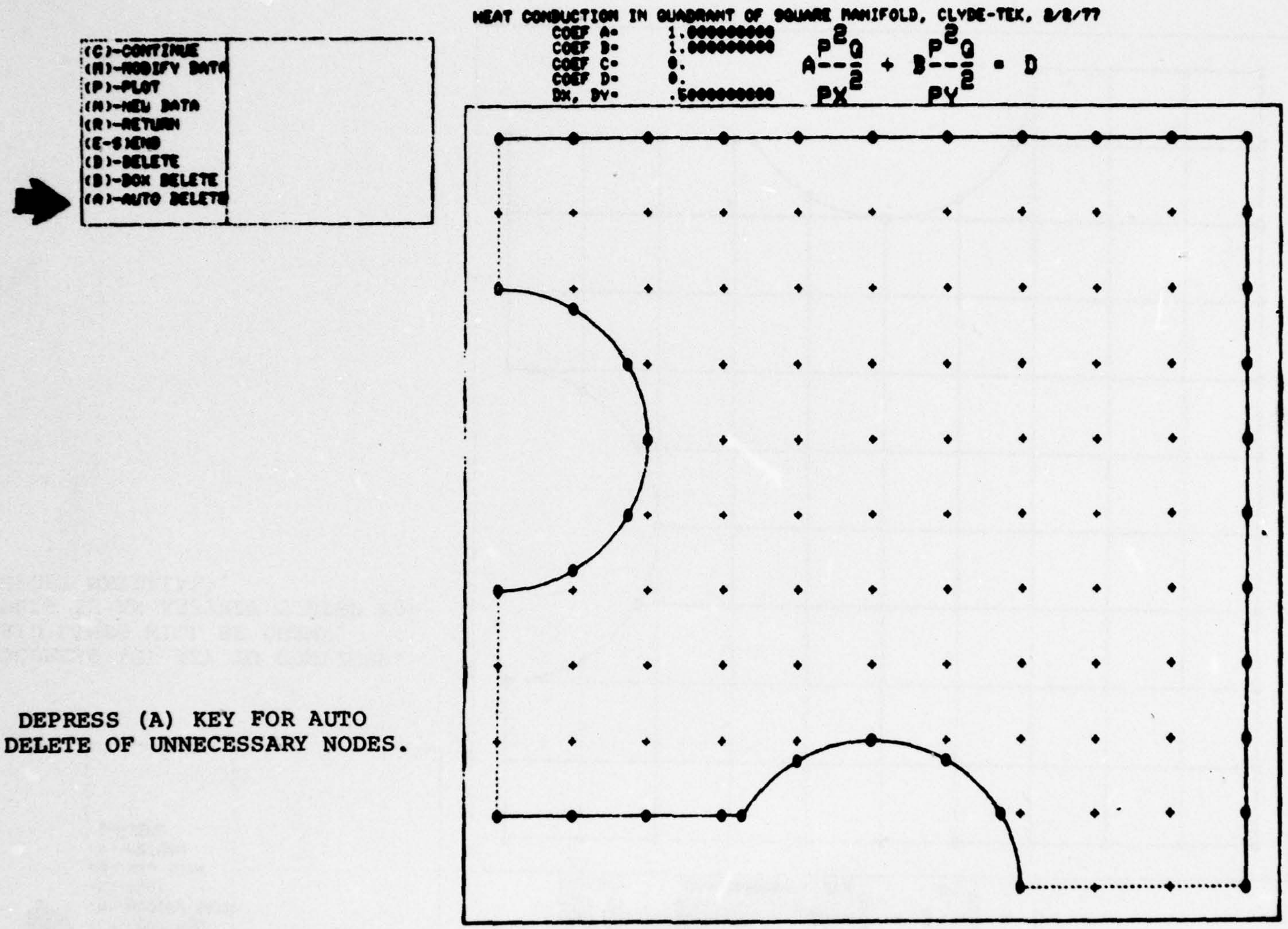
HEAT CONDUCTION IN QUADRANT OF SQUARE MANIFOLD, CLYDE-TEX, 2/2/77

COEF A= 1.000000000
COEF B= 1.000000000
COEF C= 0.
COEF D= 0.
DX, DY= .5000000000

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



FINER GRID IS NOT DESIRED FOR THIS PROBLEM. TYPE "NO" FOLLOWED BY RETURN KEYSTROKE.



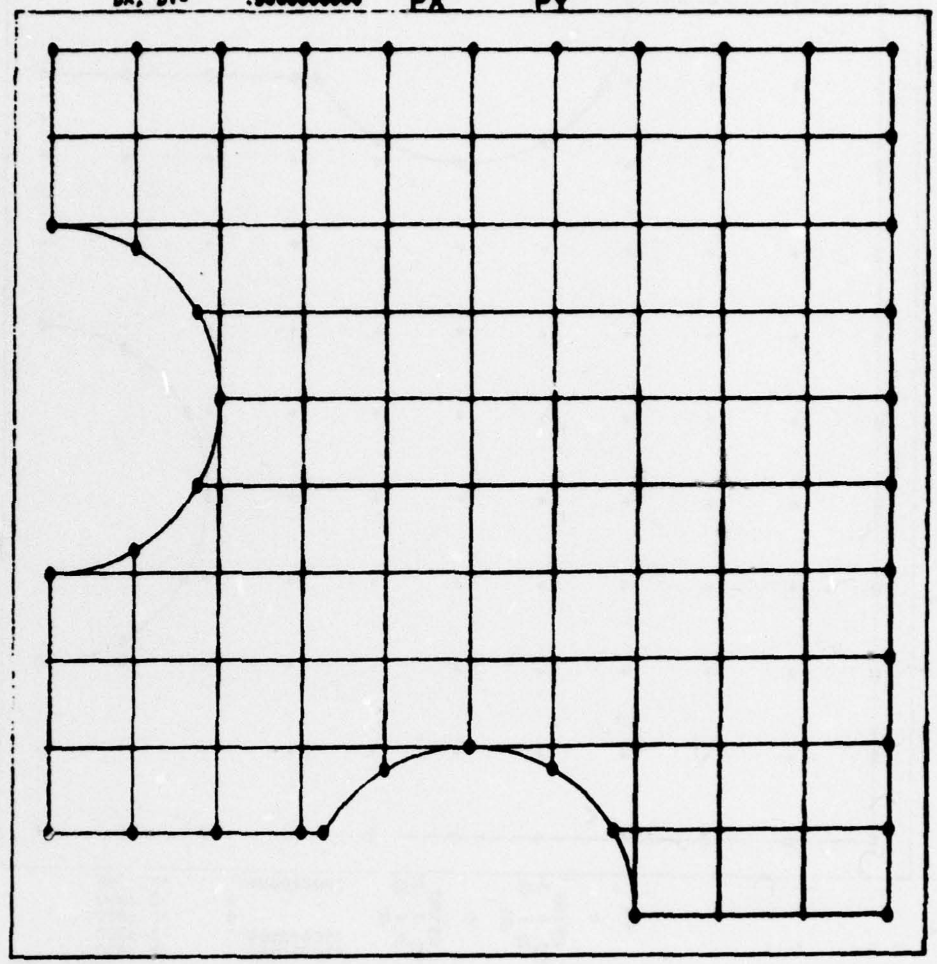
DEPRESS (A) KEY FOR AUTO
DELETE OF UNNECESSARY NODES.

HEAT CONDUCTION IN QUADRANT OF SQUARE MANIFOLD, CLYDE-TEK, 2/2/77

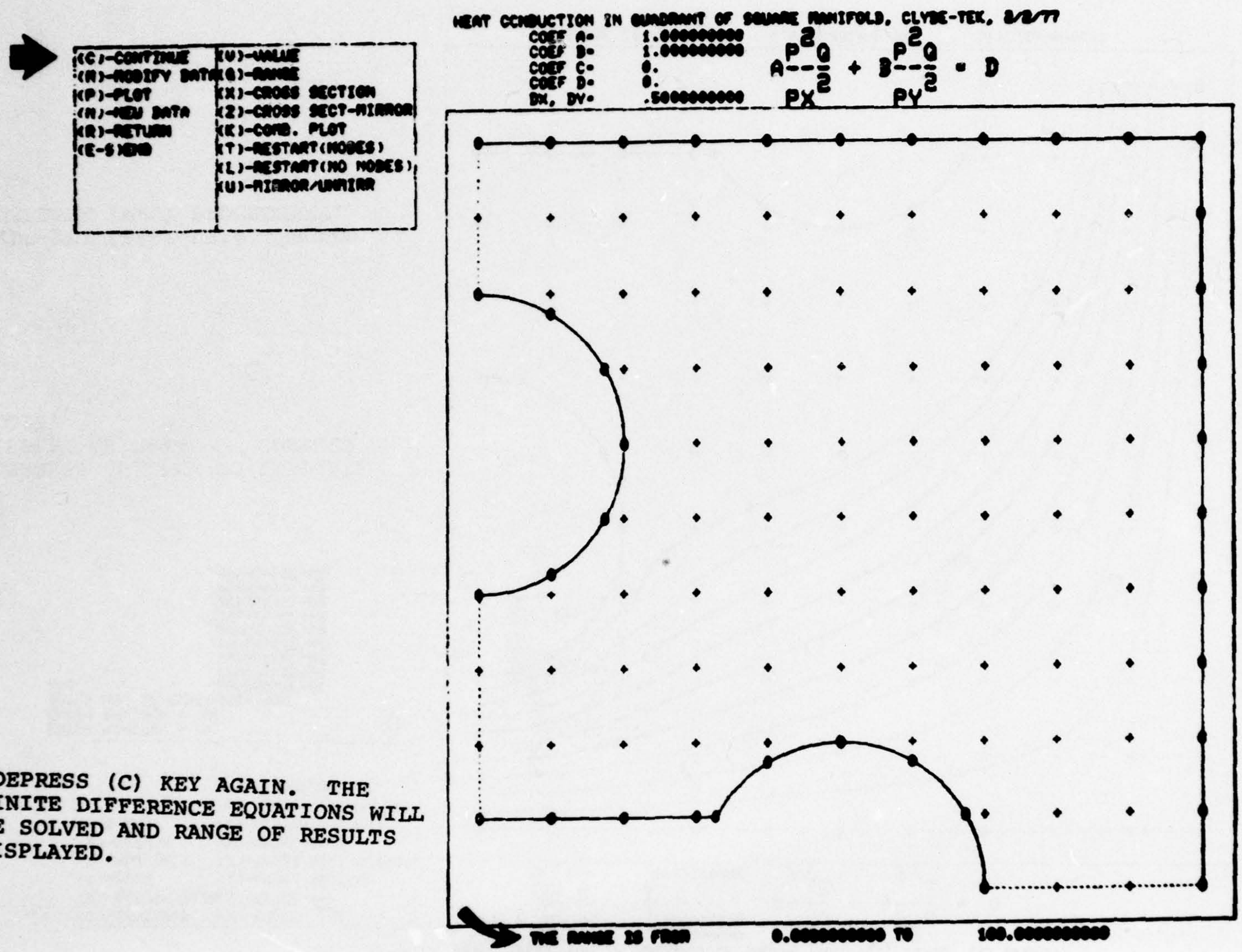
```
COEF A=   1.000000000
COEF B=   1.000000000
COEF C=   0.
COEF D=   0.
DX, DY=   .5000000000
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$

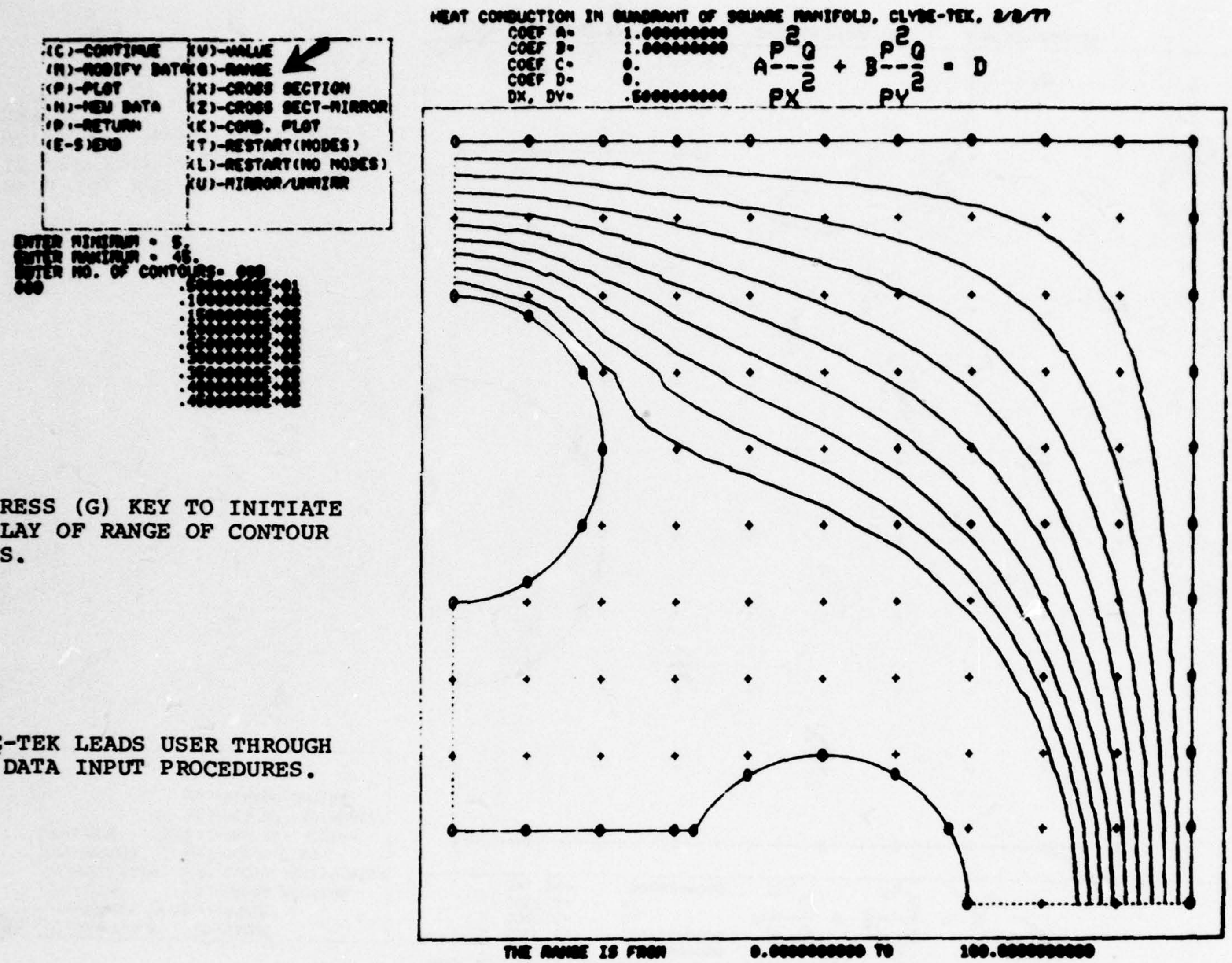
```
(C)-CONTINUE
(M)-MODIFY DATA
(P)-PLOT
(N)-NEW DATA
(R)-RETURN
(E-S)END
```



DEPRESS (C) KEY TO CONTINUE.
GRID LINES WILL BE DRAWN.
(THIS IS AN AESTHETIC STEP FOR REPORT MATERIAL).



DEPRESS (C) KEY AGAIN. THE FINITE DIFFERENCE EQUATIONS WILL BE SOLVED AND RANGE OF RESULTS DISPLAYED.

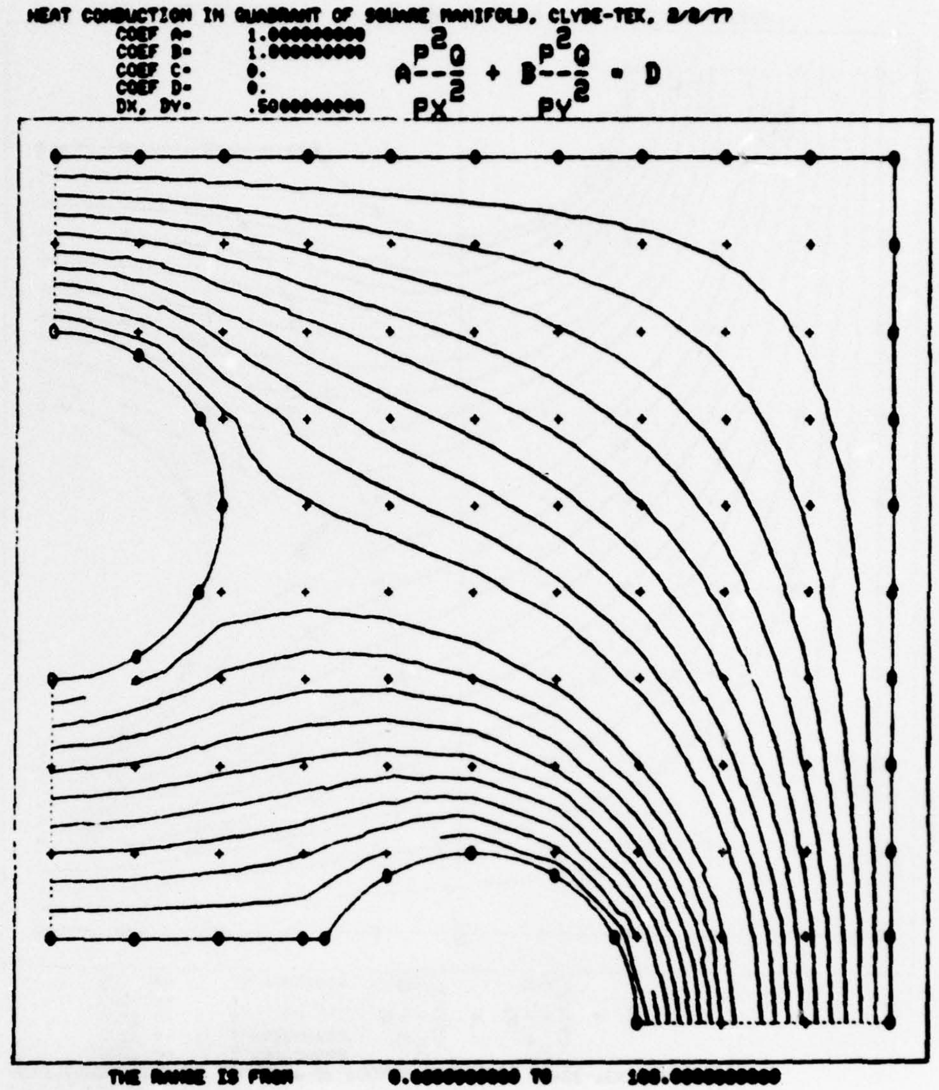


DEPRESS (G) KEY TO INITIATE DISPLAY OF RANGE OF CONTOUR PLOTS.

CLYDE-TEK LEADS USER THROUGH "RANGE" DATA INPUT PROCEDURES.

```
(C)-CONTINUE      (V)-VALUE
(M)-MODIFY DATA   (G)-RANGE
(P)-PLOT          (X)-CROSS SECTION
(N)-NEW DATA      (Z)-CROSS SECT-MIRROR
(P)-RETURN        (K)-COMB. PLOT
(E-S)END          (T)-RESTART(NODES)
                  (L)-RESTART(NO NODES)
                  (U)-MIRROR/UNMIRR

ENTER MINIMUM : 5.
ENTER MAXIMUM : 45.
ENTER NO. OF CONTOURS:
```

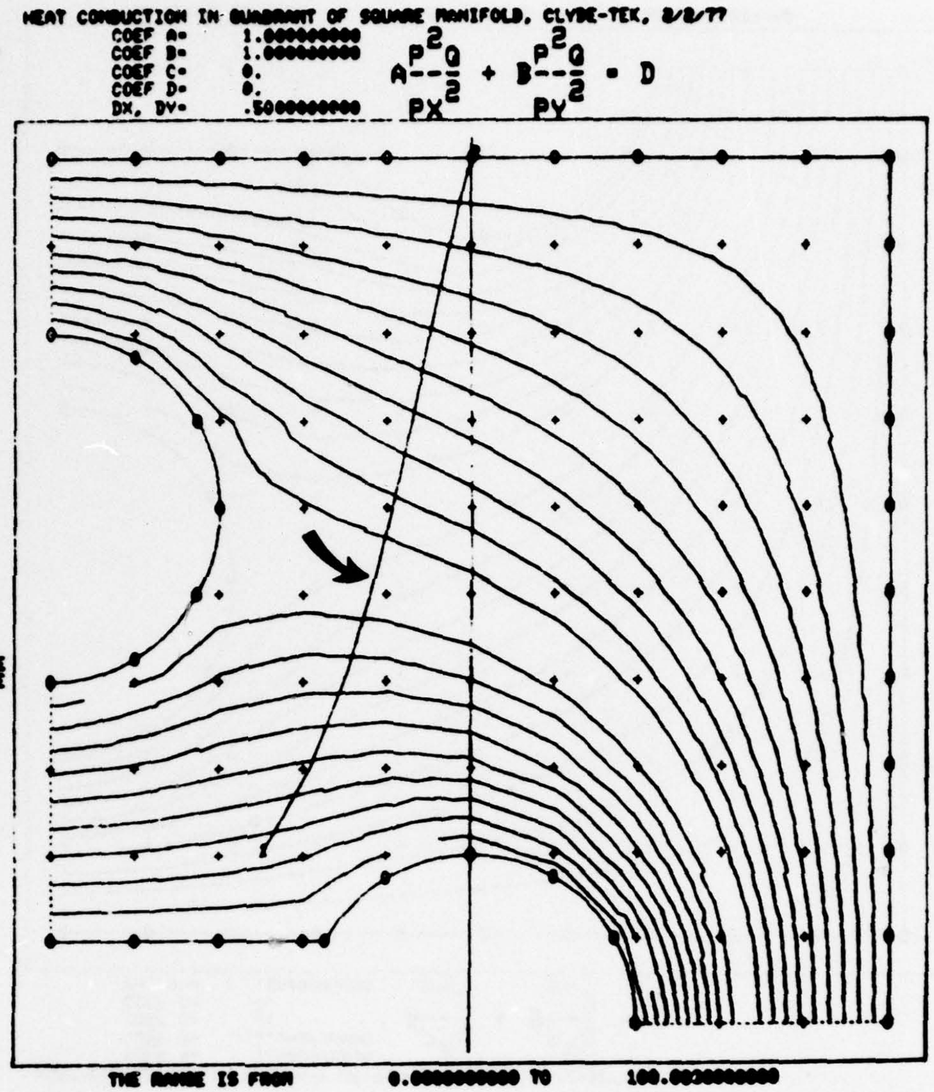
```
ENTER MINIMUM :
ENTER MAXIMUM :
ENTER NO. OF CONTOURS:
```

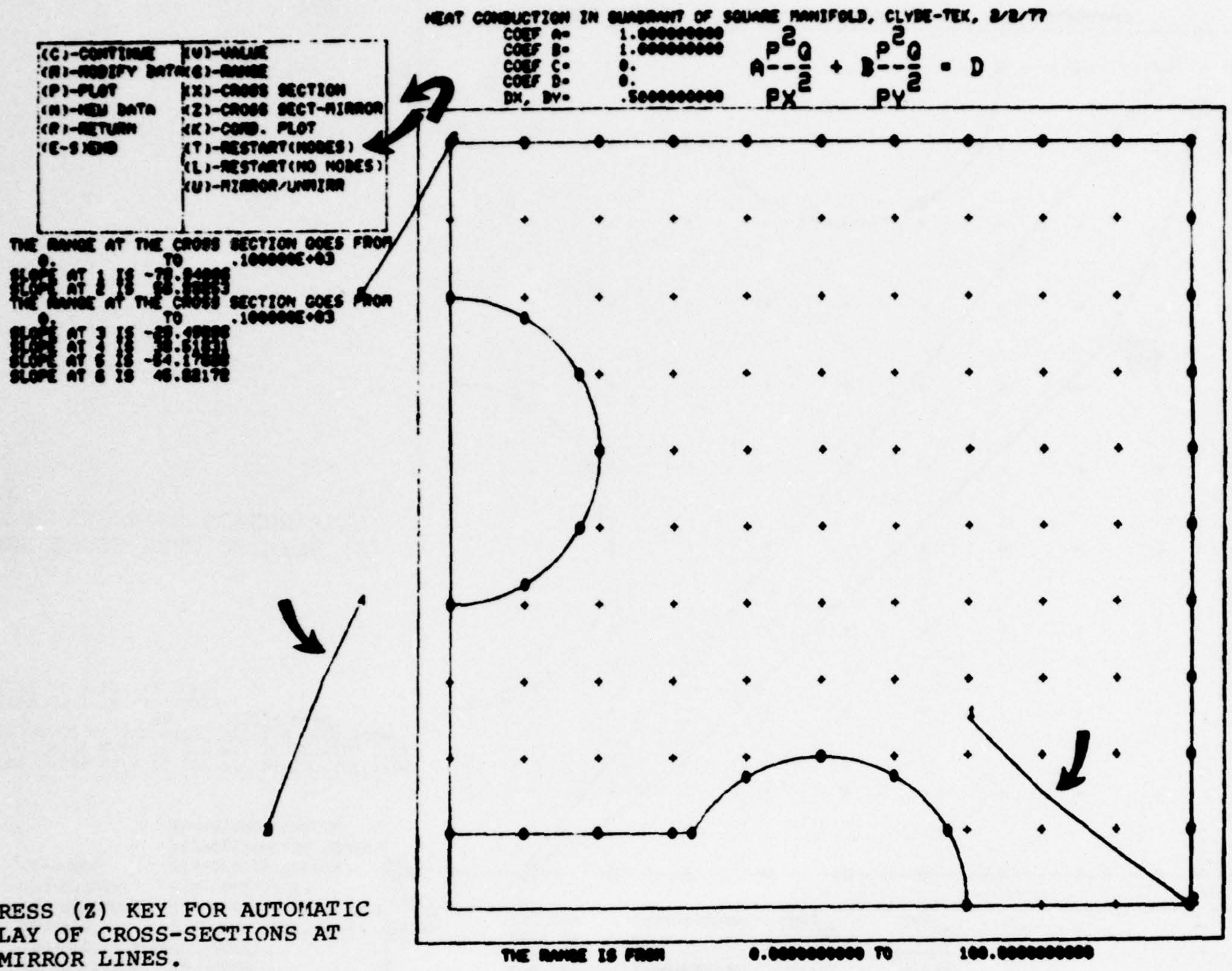


MORE CONTOUR PLOTS CALLED FOR.

```
(C)-CONTINUE      (V)-VALUE
(M)-MODIFY DATA   (G)-RANGE
(P)-PLOT          (X)-CROSS SECTION
(N)-NEW DATA      (Z)-CROSS SECT-MIRROR
(P)-RETURN        (K)-COMB. PLOT
(E-S)END          (T)-RESTART(NODES)
                  (L)-RESTART(NO NODES)
                  (U)-MIRROR/UNMIRR

ENTER MINIMUM : 5.
ENTER MAXIMUM : 45.
ENTER NO. OF CONTOURS: 009
009
[illegible]

ENTER MINIMUM : 55.
ENTER MAXIMUM : 95.
ENTER NO. OF CONTOURS: 009
009
[illegible]

MOVE CROSS HAIR TO 1ST PT. OF CUTTING LINE
MOVE CROSS HAIR TO 2ND PT. OF CUTTING LINE
THE RANGE AT THE CROSS SECTION GOES FROM
  0.            TO       .100000E+03
SLOPE AT 1 IS -46.22381
SLOPE AT 2 IS  18.90831
```

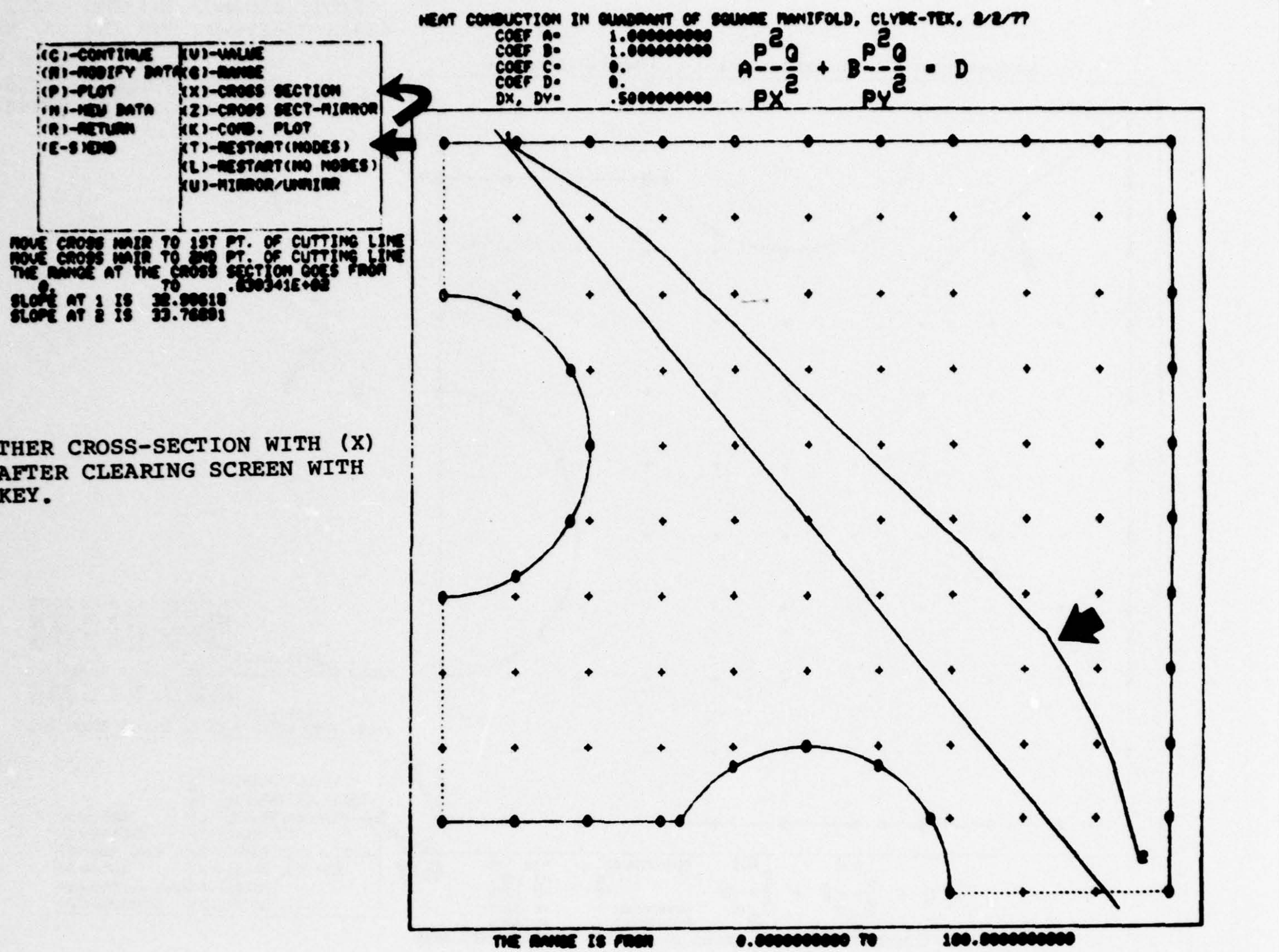
DEPRESS (X) KEY FOR CROSS-SECTION DISPLAY. FOLLOW CLYDE-TEK'S INSTRUCTIONS.



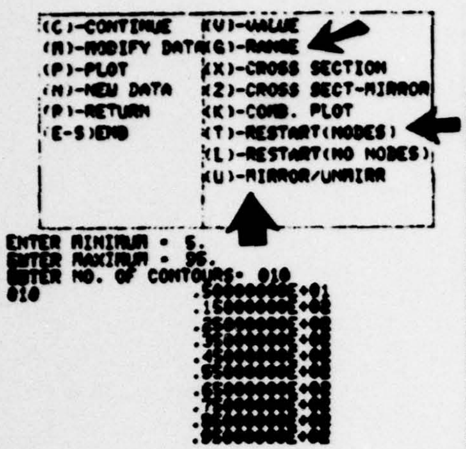


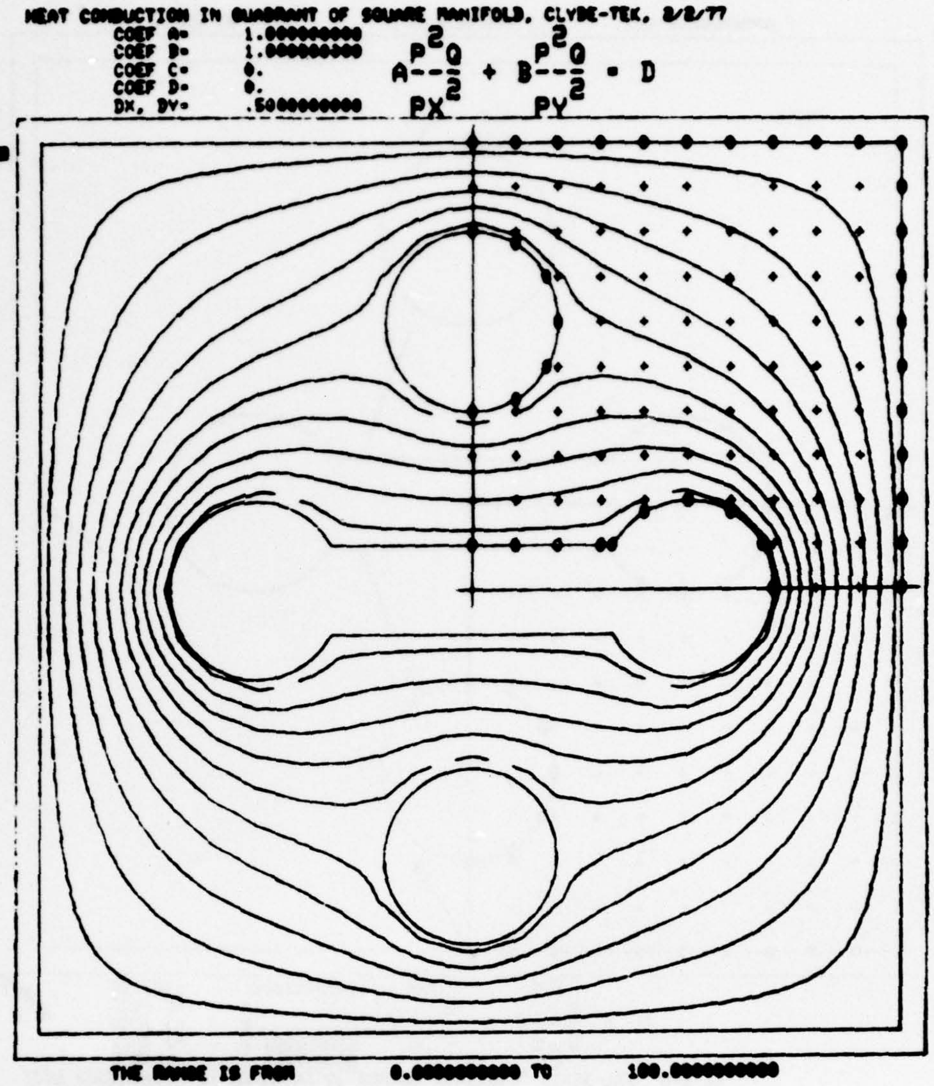
DEPRESS (Z) KEY FOR AUTOMATIC DISPLAY OF CROSS-SECTIONS AT ALL MIRROR LINES.

THE (T) KEY WAS DEPRESSED FIRST TO CLEAR OFF THE CONTOUR PLOTS.



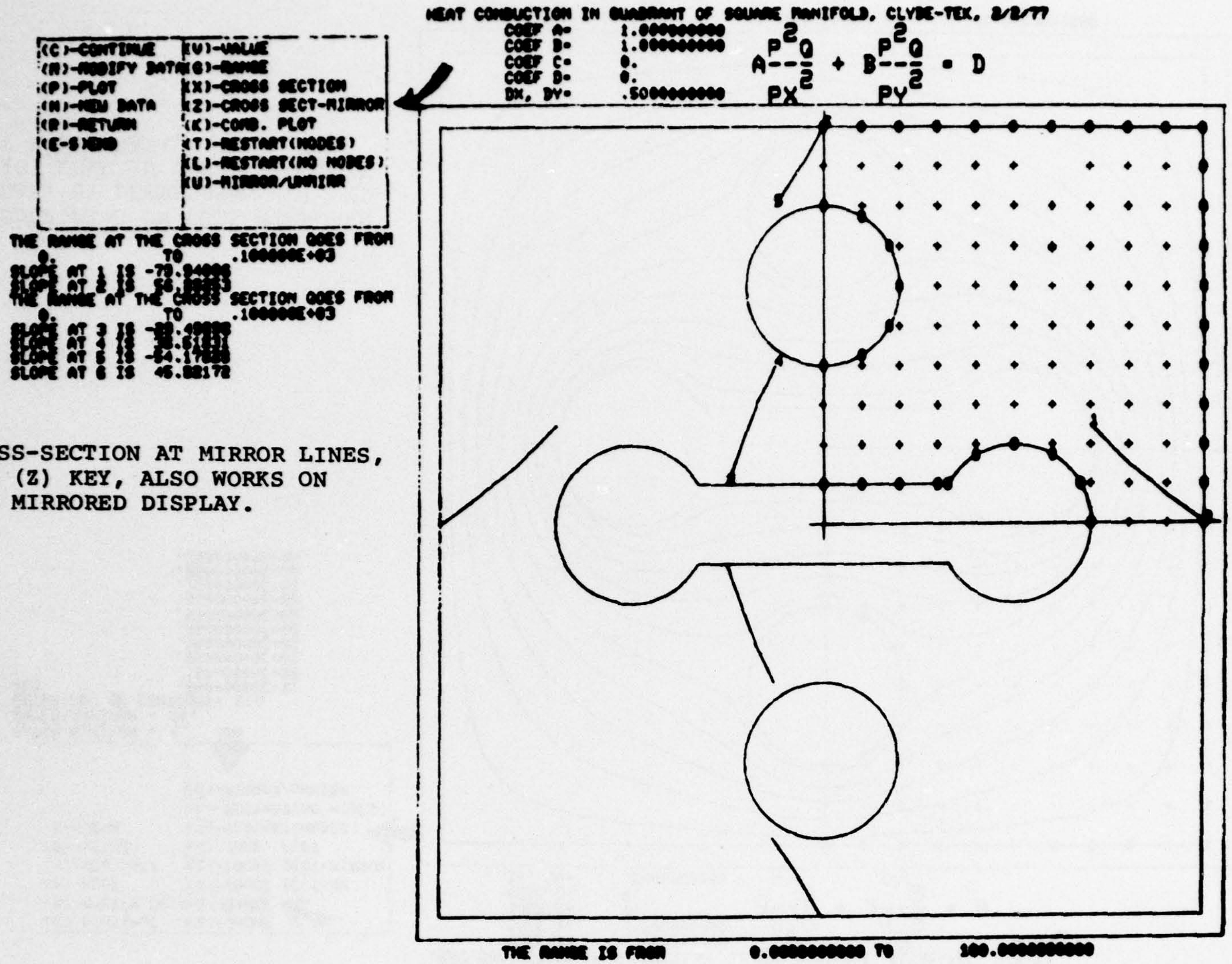
ANOTHER CROSS-SECTION WITH (X) KEY AFTER CLEARING SCREEN WITH (T) KEY.



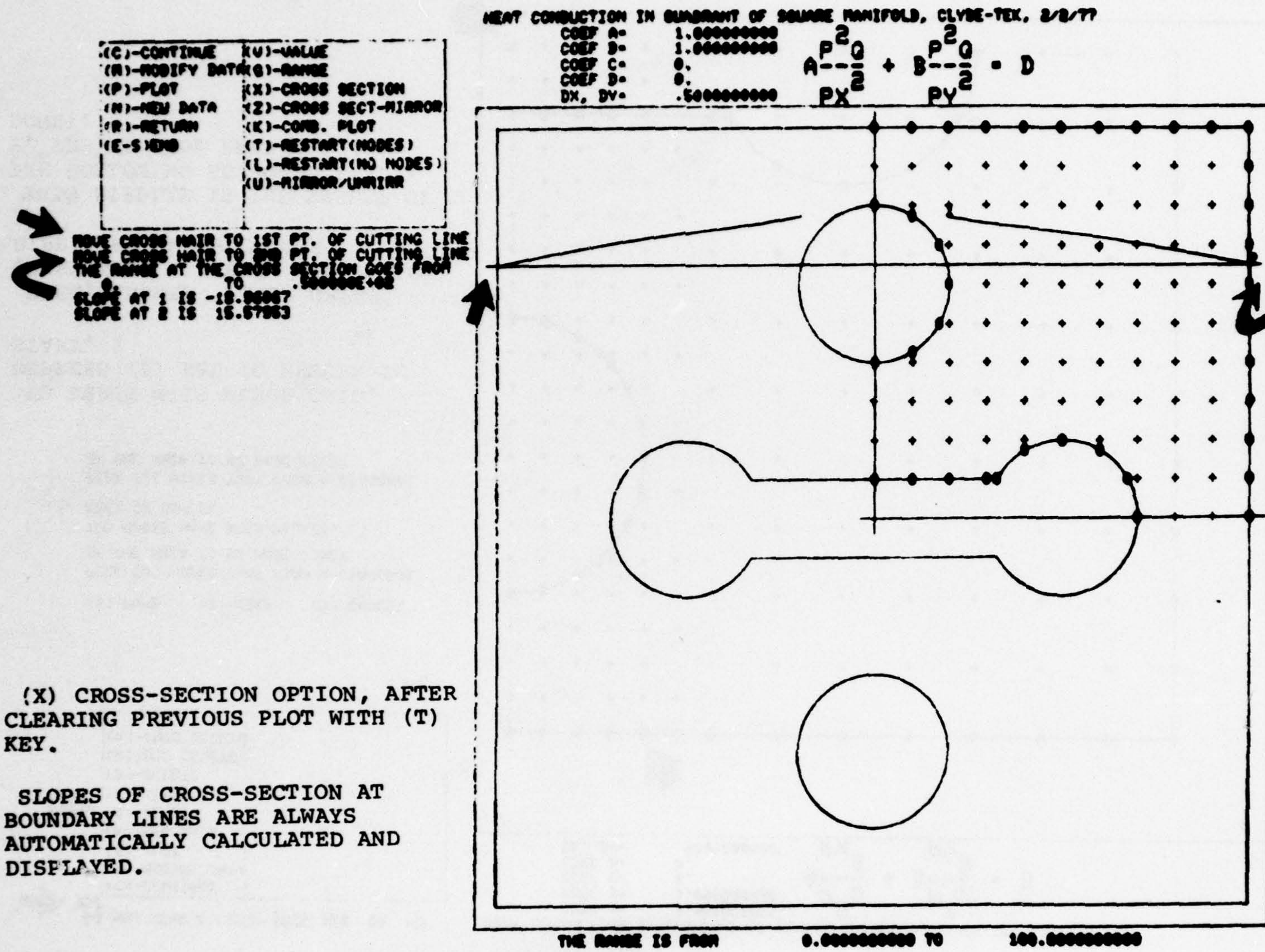


$$A\frac{\partial^2 Q}{\partial X^2} + B\frac{\partial^2 Q}{\partial Y^2} = D$$

CONTOUR MAPS ON FULL MIRRORED DISPLAY, BY DEPRESSING (U), (T), AND (G) KEYS IN ORDER AND THEN INPUT RANGE DATA.



CROSS-SECTION AT MIRROR LINES, WITH (Z) KEY, ALSO WORKS ON FULL MIRRORED DISPLAY.



(X) CROSS-SECTION OPTION, AFTER CLEARING PREVIOUS PLOT WITH (T) KEY.

SLOPES OF CROSS-SECTION AT BOUNDARY LINES ARE ALWAYS AUTOMATICALLY CALCULATED AND DISPLAYED.

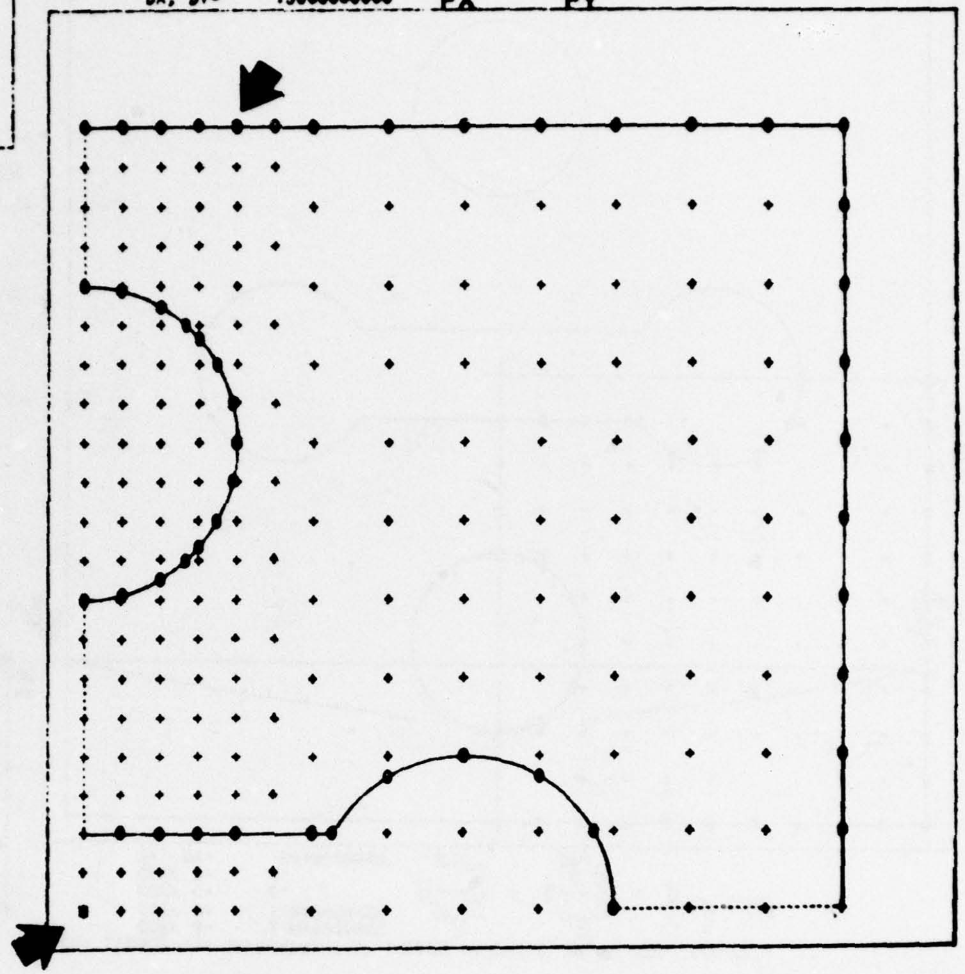
DO YOU WISH A FINER GRID YES OR NO
YES

(C)-CONTINUE
(M)-MODIFY DATA
(P)-PLOT
(N)-NEW DATA
(R)-RETURN
(E-S)END
(D)-DELETE
(B)-BOX DELETE
(A)-AUTO DELETE

HEAT CONDUCTION IN QUADRANT OF SQUARE MANIFOLD, CLYDE-TEX, 2/2/77

COEF A= 1.000000000
COEF B= 1.000000000
COEF C= 0.
COEF D= 0.
DX, DY= .5000000000

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



(1)-DONE (2)-KEEP (3) CANCEL

PICK TWO NODES THAT FORM A DIAGONAL OF THE AREA TO BE MADE FINER

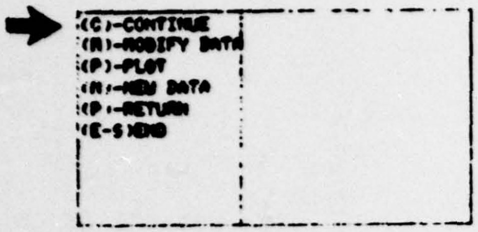
TWO NODES HAVE BEEN PICKED, KEEP OR CANCEL

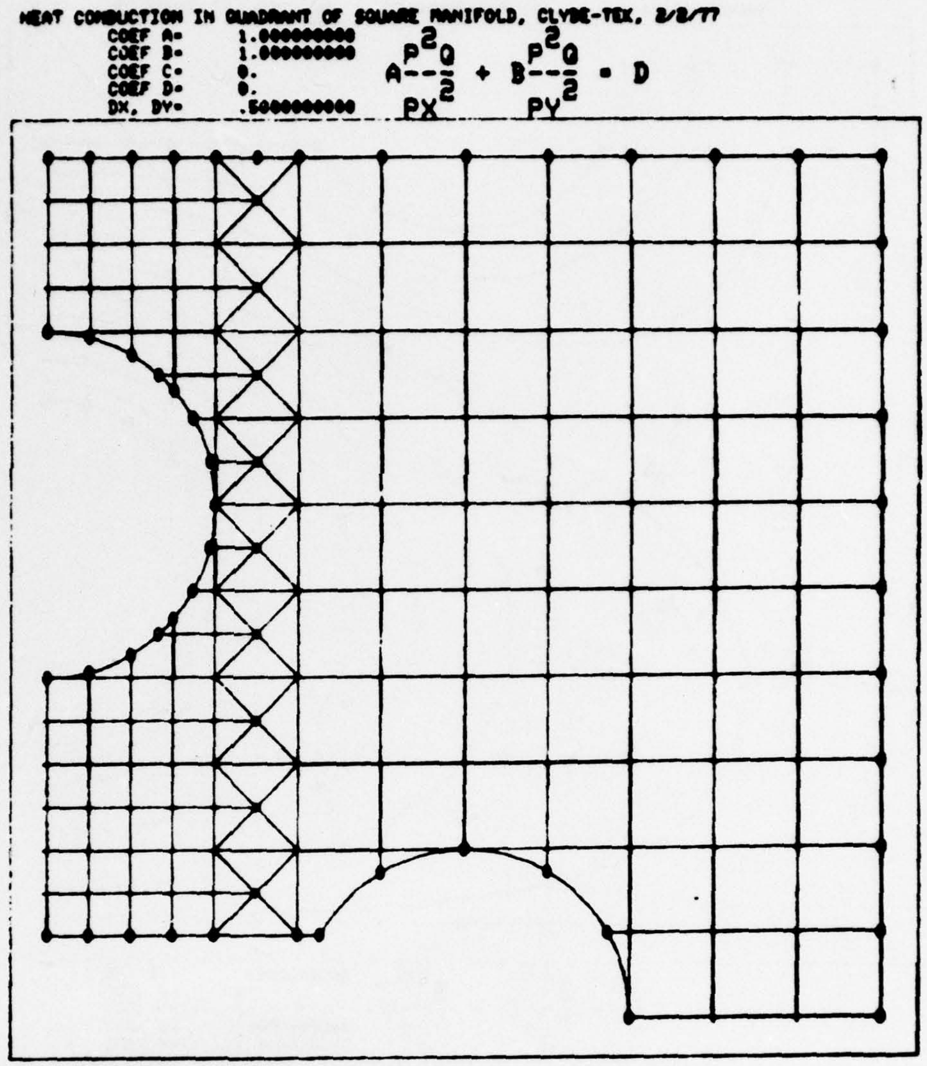
PICK TWO NODES THAT FORM A DIAGONAL OF THE AREA TO BE MADE FINER

TO RERUN WITH FINER GRID, DEPRESS (R) KEY TO RETURN TO START.

THEN, ANSWER "FINER GRID?" QUERY WITH A "YES", AND FOLLOW DISPLAYED INSTRUCTIONS.

THIS DISPLAY IS THE RESULT OF THE FOLLOWING KEYBOARD INPUT: R, "YES", 2 (for KEEP), 1 (for DONE).





KEY (A) FOR AUTO DELETE, THEN
(C) FOR CONTINUE.

```
(C)-CONTINUE      (U)-VALUE
(M)-MODIFY DATA   (G)-RANGE
(P)-PLOT          (X)-CROSS SECTION
(N)-NEW DATA      (Z)-CROSS SECT-MIRROR
(R)-RETURN        (K)-COMB. PLOT
(E-S)END          (T)-RESTART(NODES)
                  (L)-RESTART(NO NODES)
                  (U)-MIRROR/UNMIRR

ENTER MINIMUM = 10.0
ENTER MAXIMUM = 90.0
ENTER NO. OF CONTOURS= 009
0090
                    .10000000E+02
                    .20000000E+02
                    .30000000E+02
                    .40000000E+02
                    .50000000E+02
                    .60000000E+02
                    .70000000E+02
                    .80000000E+02
                    .90000000E+02
```

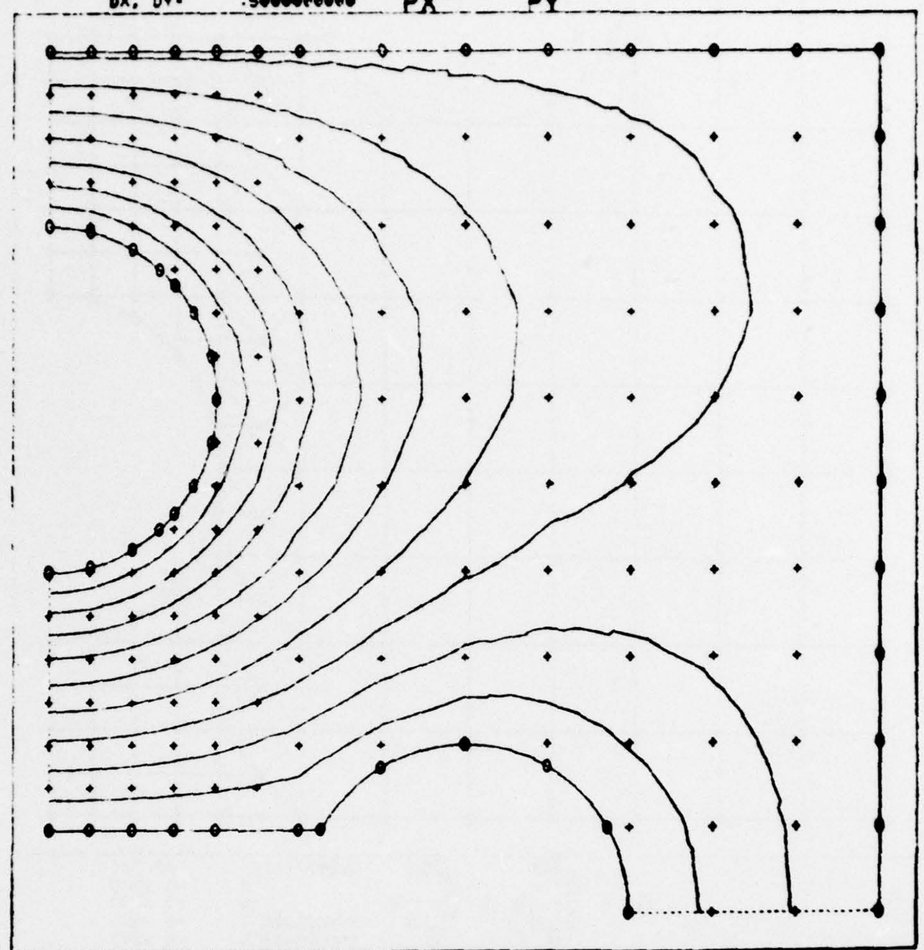
KEY (C) FOR SOLUTION, THEN (G) TO INITIATE RANGE OF CONTOURS.

(HERE, BOUNDARY TEMPERATURES HAD BEEN CHANGED TO $T_1 = 72^o$ F, $T_2 = 0^o$ F, $T_3 = 100^o$ F)

HEAT CONDUCTION IN QUADRANT OF SQUARE MANIFOLD, CLYDE-TEX, 2/2/77

COEF A=	1.000000000
COEF B=	1.000000000
COEF C=	0.
COEF D=	0.
DX, DY=	.5000000000

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



THE RANGE IS FROM 0.0000000000 TO 100.0000000000

IBM

FORTRAN Coding Form

GX28-7327-6 U/M 050**
Printed in U.S.A.

PROGRAM: CLYDE BATCH CONTROL CARDS (WITH OPTIONAL CALCOMP PLOT & TEKTRONIX PRE-VIEW PLOT DISPLAY CARDS)*

```
[illegible] ← [illegible] punch in column 1)
[illegible]1.                      ← (Your job card)
[illegible]([illegible]),[illegible]     ← (See Digital Systems Hand-book)

PURGE,II,ISAKOWER,CY=1,ID=ISAKOWER.
PURGE,XX.
EXIT.
MODE,0.
[illegible],ID=[illegible].
REQUEST,REBEL,*PF.
REQUEST,TAPE77,NT,S. PLOT TAPE/BLANK PAPER/ISAKOWER ← (For Calcomp Plot) *
LDSET(LIB=IGS274)
[illegible].
CATALOG,REBEL,CLYDE[illegible],ID=ISAKOWER,CY=1.  ← (For Passive Tektronix Display)*
[illegible]
7/8/9 ← (multiple 7,8,9 punch in column 1)

{CLYDE BATCH INPUT DATA CARDS}

6/7/8/9 ← (multiple 6,7,8,9 punch in column 1)
```

*A standard card form, IBM electro 888157, is available for punching statements from this form

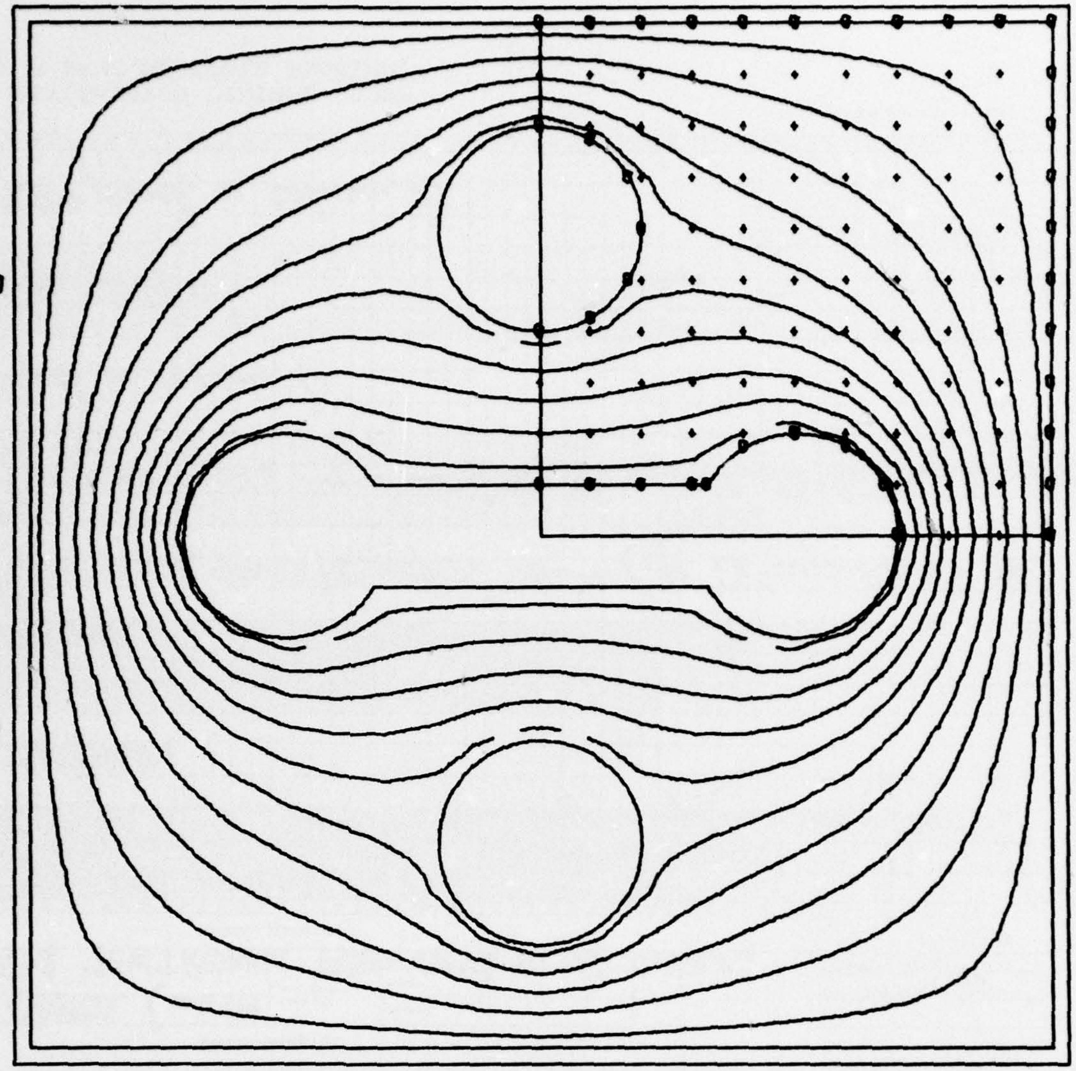
**Number of forms per pad may vary slightly

CLYDE-BATCH CONTROL CARDS
FOR SAME MANIFOLD PROBLEM.

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$

COEF A=	1.000000000
COEF B=	1.000000000
COEF C=	0.000000000
COEF D=	0.000000000
DX,DY =	.500000000
RANGE IS	0.000000 TO 100.000000
CONTOUR VALUE	5.0000000
CONTOUR VALUE	15.0000000
CONTOUR VALUE	25.0000000
CONTOUR VALUE	35.0000000
CONTOUR VALUE	45.0000000
CONTOUR VALUE	55.0000000
CONTOUR VALUE	65.0000000
CONTOUR VALUE	75.0000000
CONTOUR VALUE	85.0000000
CONTOUR VALUE	95.0000000

CALCOMP OUTPUT PLOT OF MANIFOLD TEMPERATURE CONTOURS.

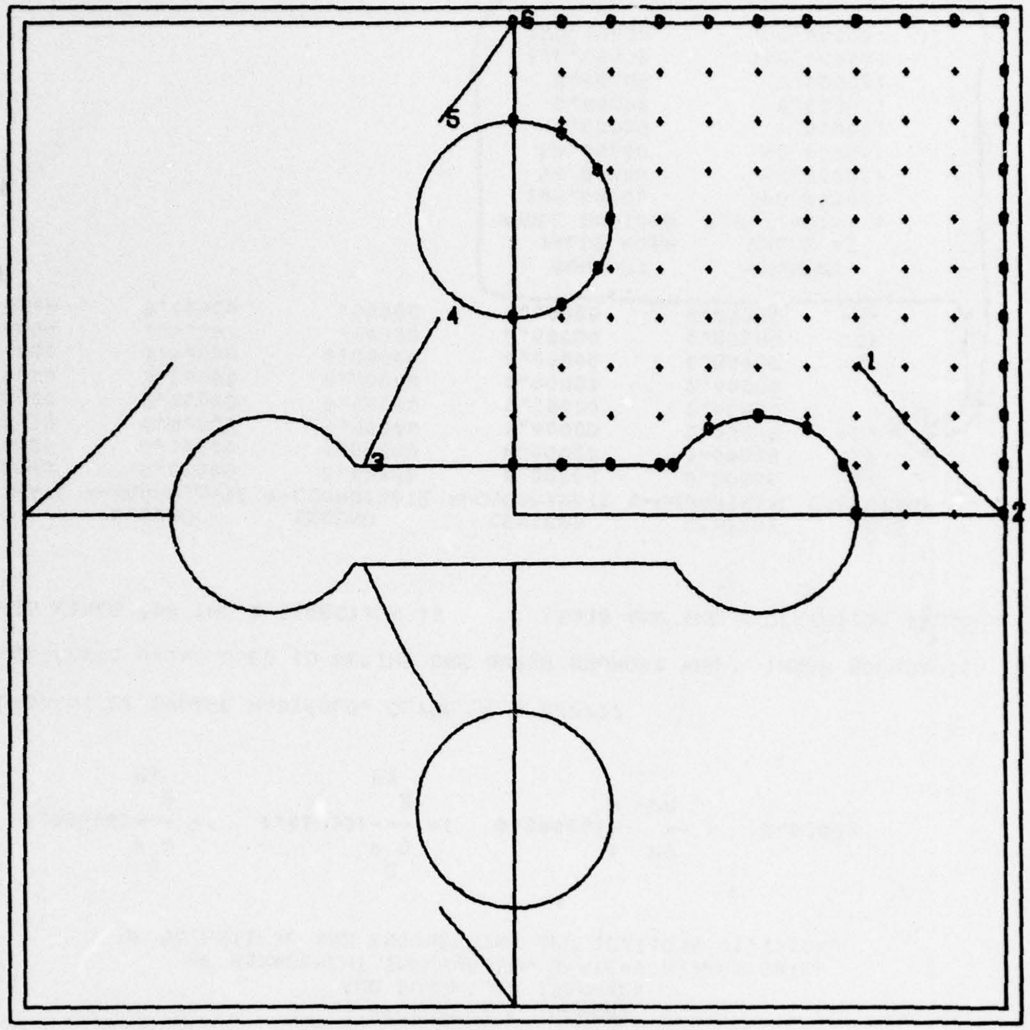


HEAT CONDUCTION IN QUADRANT OF SQUARE MANIFOLD, CLYDE-TEK, 2/2/77

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$

```
COEF A=         1.0000000000
COEF B=         1.0000000000
COEF C=         0.0000000000
COEF D=         0.0000000000
DX,DY =          .5000000000
RANGE IS     0.000000 TO  100.000000
CROSS SECTION LINE
( 0.          ,  .250000E-04 TO
  .600000E+01,  .250000E-04 )
CROSS SECTION RANGE IS
        0.000000 TO  100.000000
SLOPE AT 1 IS -79.94006
SLOPE AT 2 IS  66.88253
CROSS SECTION LINE
(  .250000E-04 , 0.            TO
  .250000E-04,  .600000E+01 )
CROSS SECTION RANGE IS
        0.000000 TO  100.000000
SLOPE AT 3 IS -29.49898
SLOPE AT 4 IS  38.51831
SLOPE AT 5 IS -54.17828
SLOPE AT 6 IS  45.82172
```

CALCOMP OUTPUT PLOT OF CROSS-SECTION OF MANIFOLD TEMPERATURES AT MIRROR LINES.



HEAT CONDUCTION IN QUADRANT OF SQUARE MANIFOLD. CLYDE-TEK. 2/2/77

TYPICAL CLYDE-BATCH OUTPUT LISTING.

CLYDE- VERSION 1 - 3/1/77:

BY ROBERT E. BARNAS :
AND ROBERT I. ISAKOWER
OF MANAGEMENT INFORMATION SYSTEMS DIRECTORATE,
OF SCIENTIFIC AND ENGINEERING APPLICATIONS DIVISION.

$$(1.00000)\frac{P^{2}Q}{PX^{2}} +(1.00000)\frac{P^{2}Q}{PY^{2}} +(0.00000)\frac{1}{R}\frac{PQ}{PR} = 0.00000$$

HEAT CONDUCTION IN QUADRANT OF SQUARE MANIFOLD, CLYDE -B , 2/2/77

THERE ARE 8 CONTOUR SEGMENTS BEING USED TO DEFINE ONE OUTER BOUNDRY AND INNER BOUNDARIES

THE SPACING BETWEEN GRID LINES FOR THE X DIRECTION IS .5000 AND THE Y DIRECTION IS .50(

NO.	TYPE	FIRST X-COORDINATE	FIRST Y-COORDINATE	SECOND X-COORDINATE	SECOND Y-COORDINATE	CENTERS X-COORDINATE	CENTERS Y-COORDINATE	ARCS DIRECTION	BOUNDRY VALUE OVER WHOLE CONTOUR	BOUNDRY VALUE AT FIRST POINT :
1	ML	0.00000	.50000	0.00000	2.00000	0.00000	0.00000	-0.	100.00000	100.00000:
2	CA	0.00000	2.00000	0.00000	4.00000	0.00000	3.00000	CCW	50.00000	50.00000:
3	ML	0.00000	4.00000	0.00000	5.00000	0.00000	0.00000	-0.	50.00000	50.00000:
4	SL	0.00000	5.00000	5.00000	5.00000	0.00000	0.00000		0.00000	0.00000:
5	SL	5.00000	5.00000	5.00000	0.00000	0.00000	0.00000		0.00000	0.00000:
6	ML	5.00000	0.00000	3.50000	0.00000	0.00000	0.00000	-0.	0.00000	0.00000:
7	CA	3.50000	0.00000	1.63397	.50000	2.50000	0.00000	CCW	100.00000	100.00000:
8	SL	1.63397	.50000	0.00000	.50000	0.00000	0.00000	-0.	100.00000	100.00000:

CLYDE- VERSION 1 - 3/1/77:

BY ROBERT E. BARNAS :
AND ROBERT I. ISAKOWER
OF MANAGEMENT INFORMATION SYSTEMS DIRECTORATE,
SCIENTIFIC AND ENGINEERING APPLICATIONS DIVISION.

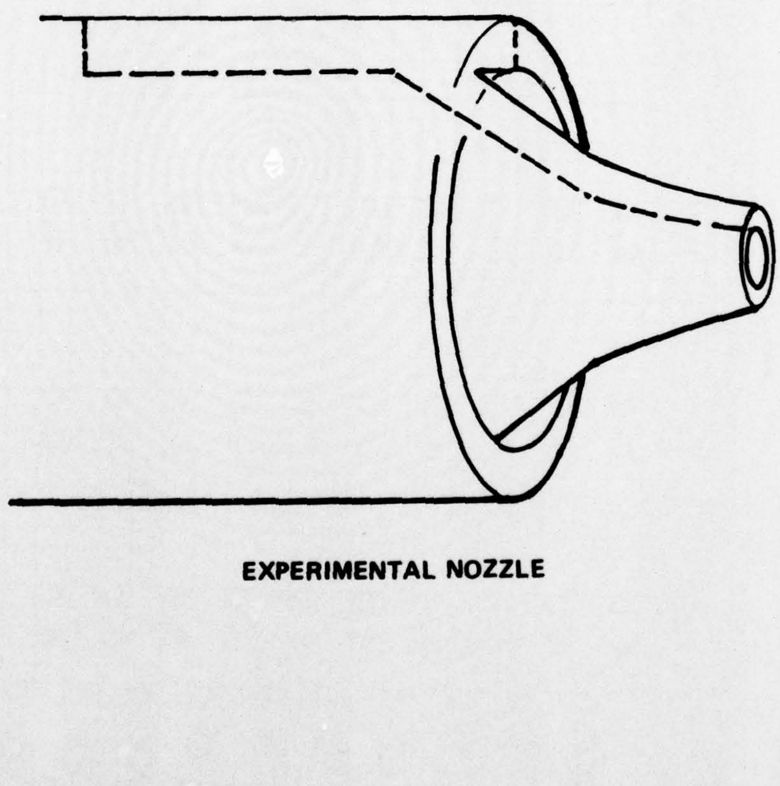
HEAT CONDUCTION IN QUADRANT OF SQUARE MANIFOLD, CLYDE -B , 2/2/77

NUMBER OF NODE	X-COORDINATE	Y-COORDINATE	NODE VALUE
1	0.00000	1.00000	85.2505107587
2	0.00000	1.50000	69.2591551446
3	0.00000	4.50000	22.9108614426
4	.50000	1.00000	85.8714439450
5	.50000	1.50000	70.8930549099
6	.50000	2.00000	54.6283941943
7	.50000	4.00000	43.3781250694
8	.50000	4.50000	20.8217228852
9	1.00000	1.00000	87.3422101114
10	1.00000	1.50000	73.8132263558
11	1.00000	2.00000	60.8479271836
12	1.00000	2.50000	51.6440036593
13	1.00000	3.50000	46.2046237624
14	1.00000	4.00000	33.3542660354
15	1.00000	4.50000	16.9979050288
16	1.50000	1.00000	89.6841701447
17	1.50000	1.50000	76.1697132184
18	1.50000	2.00000	63.3060845249
19	1.50000	2.50000	52.9867116997
20	1.50000	3.00000	45.6143203578
69	4.50000	2.50000	[illegible]
70	4.50000	3.00000	6.4046555521
71	4.50000	3.50000	4.1606696302
72	4.50000	4.00000	2.0511401976
73	4.50000	4.50000	
74	4.50000		
75			

STEADY-STATE TEMPERATURE DISTRIBUTION (R,Z *coordinates*)

It is necessary to know the steady-state temperature distribution within the walls of an experimental convergent nozzle of a sled rocket. The ambient temperature at the outer skin of the nozzle is a constant 72°F. The inner walls of the nozzle exhibit a uniform temperature of 1000°F at the combustion chamber and linearly decreasing in the converging nozzle portion to 300°F at the throat. The wall of the cylindrical combustion chamber has temperatures varying radially from 1000°F at the inside to 72°F at the outside. The temperatures within the wall at the throat vary from 300°F on the inside to 72°F at the outside skin. The problem, similar to that of the manifold, is to calculate and plot the thermal profiles within the walls of the chamber-nozzle. In cylindrical coordinates, the Z replaces the X axis of the previous problem, while R replaces the Y.

$$A \frac{\partial^2 T}{\partial Z^2} + B \frac{\partial^2 T}{\partial R^2} + \frac{C}{R} \frac{\partial T}{\partial R} = D(r,z)$$



EXPERIMENTAL NOZZLE

IBM

FORTRAN Coding Form

GX28-7327-6 U/M 050**
Printed in U.S.A.

PROGRAM: INPUT DATA CARDS - CLYDE-TEK
PROGRAMMER: CYLINDRICAL COORDINATES

```
EXP. NOZZLE-STEADY STATE HEAT CONDUCTION IN CYLINDRICAL COORDINATES, CLYDE-TEK
   10    0.20      0.25      1.0      1.0      1.0      0.0
(1)EL    0.0       4.0       0.0      5.0
    72.0     1000.0
 2 SL    0.0       5.0       5.0      5.0
    72.0     72.0
 3 SL    5.0       5.0       5.0      4.0
    72.0     72.0
 4 SL    5.0       4.0       4.5      4.0
    72.0     72.0
 5 SL    4.5       4.0       5.0      2.5
    72.0     72.0
 6 CA    5.0       2.5       7.0      1.0      9.75      5.0 CCW
    72.0     72.0
 7 EL    7.0       1.0       7.0      0.5   <-- (Exit of Nozzle)
   300.0     72.0
 8 EA    7.0       0.5       4.0      2.0      7.5       5.5 CW <-
   700.0     300.0
 9 EL    4.0       2.0       3.0      4.0                (Converging
  1000.0     700.0                                        to throat)
10 SL    3.0       4.0       0.0      4.0
  1000.0     1000.0
```

*A standard card form, IBM electro 888157, is available for punching statements from this form.

**Number of forms per pad may vary slightly

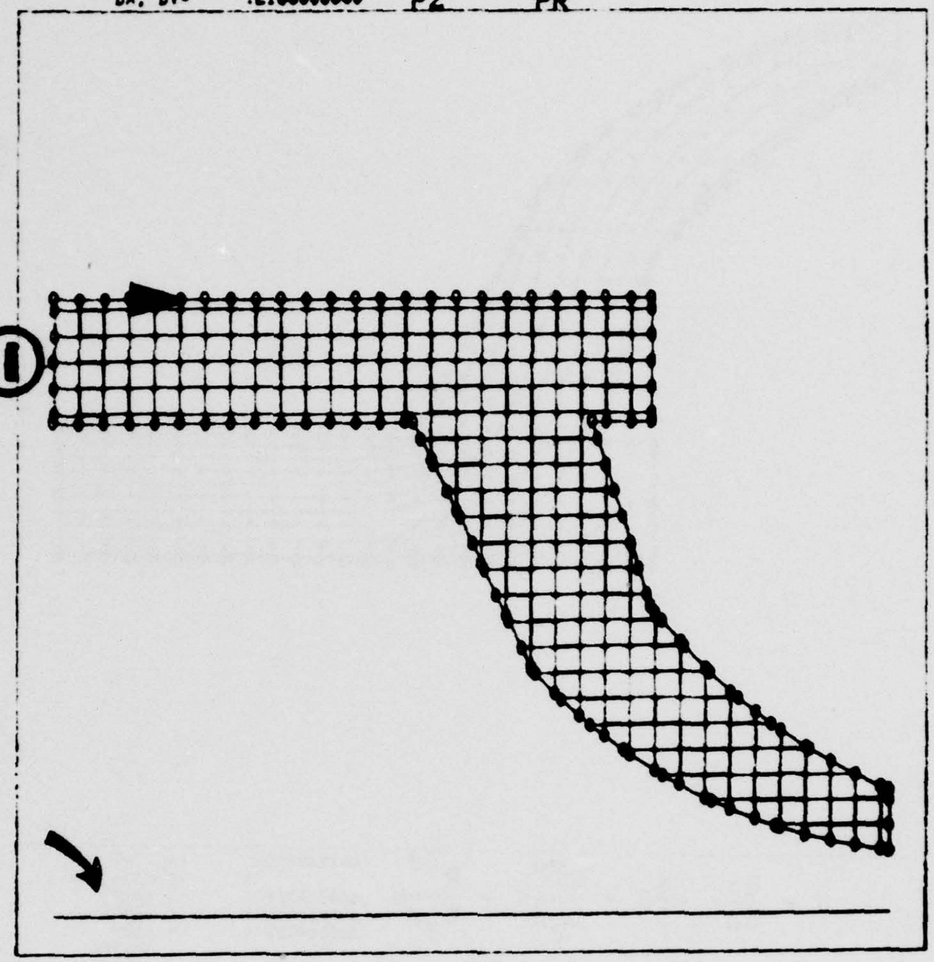
PUNCH CARD INPUT FOR CLYDE-TEK
RUN OF NOZZLE THERMAL PROBLEM.

(C)-CONTINUE
(M)-MODIFY DATA
(P)-PLOT
(N)-NEW DATA
(R)-RETURN
(E-S)END

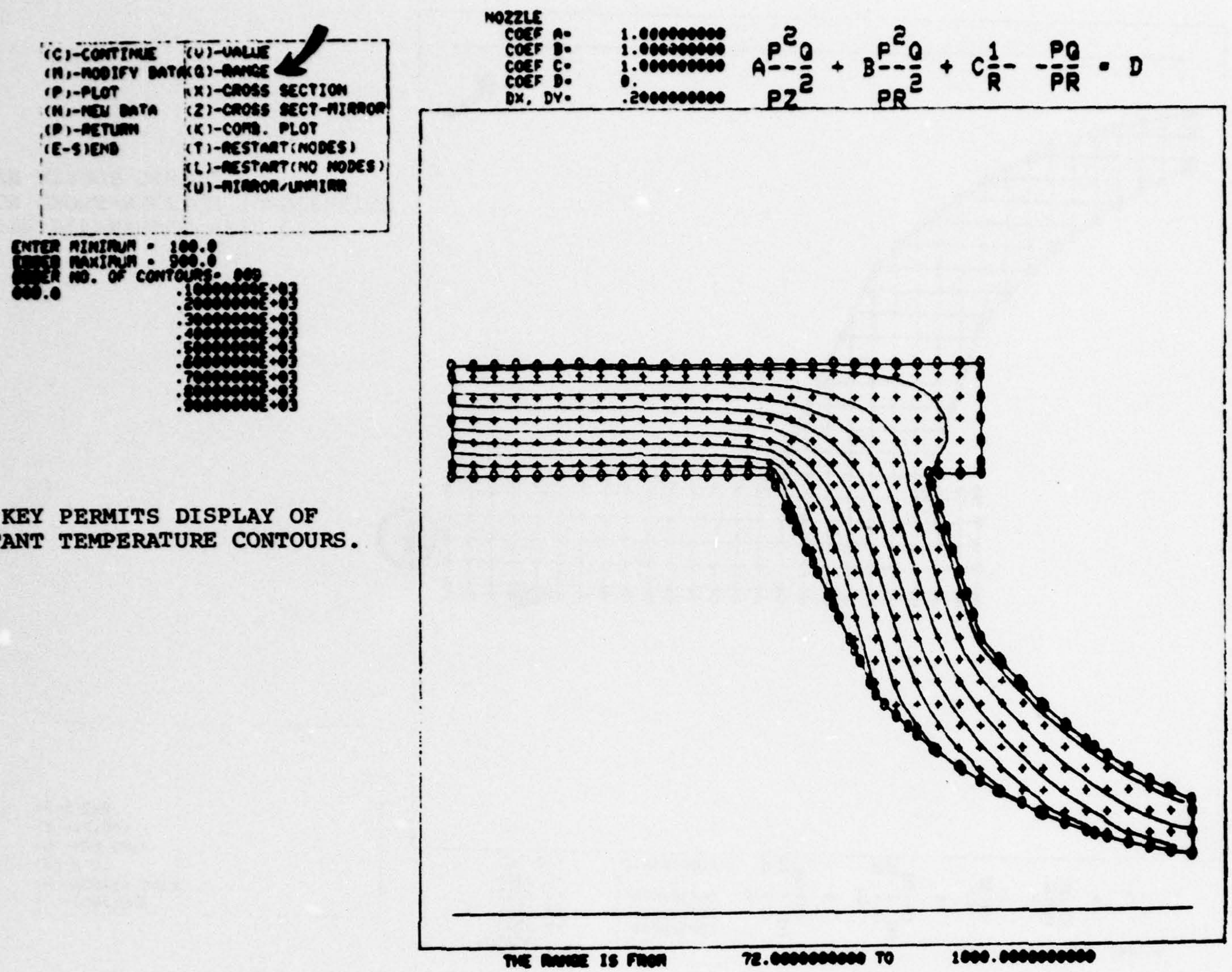
NOZZLE 000100

COEF A=	1.000000000	
COEF B=	1.000000000	
COEF C=	1.000000000	
COEF D=	0.	
DX, DY=	.2100000000	

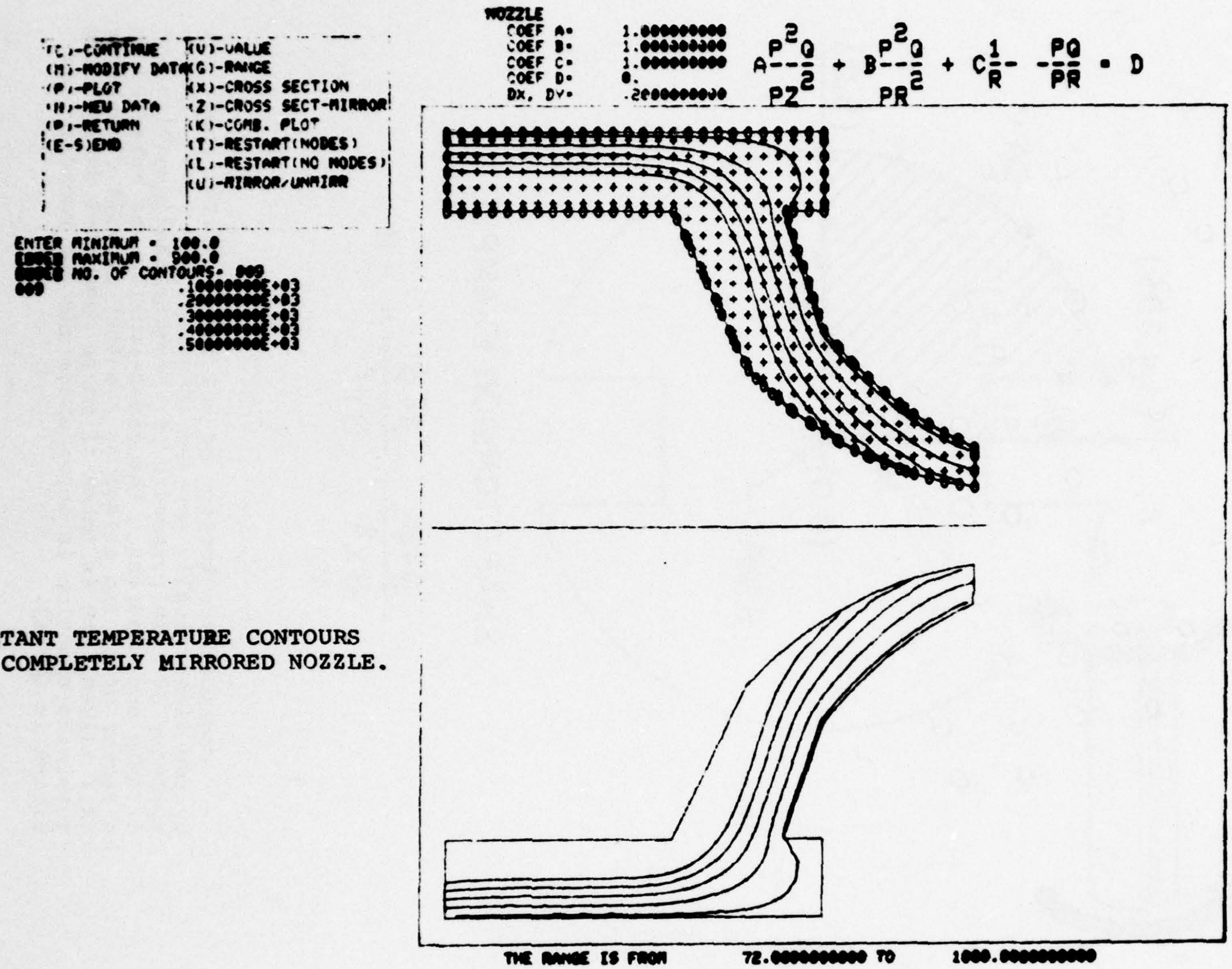
$$A\frac{P^2Q}{PZ^2} + B\frac{P^2Q}{PR^2} + C\frac{1}{R}\frac{PQ}{PR} = D$$



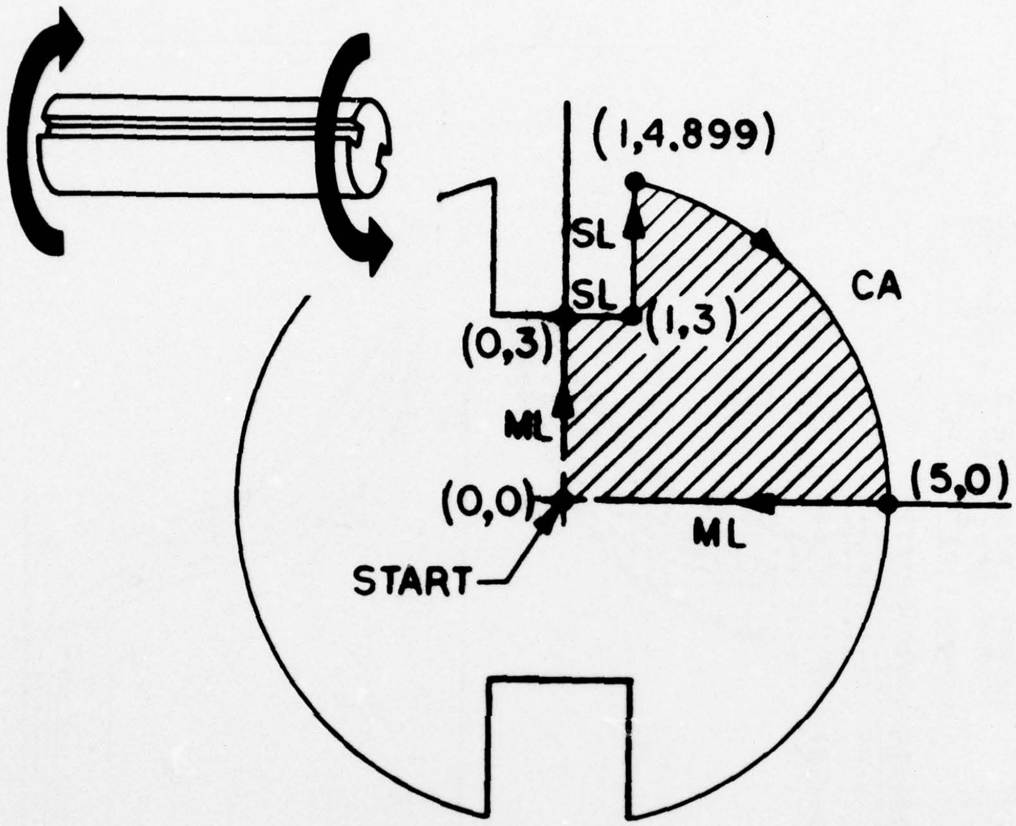
FINITE DIFFERENCE GRID OF NOZZLE CROSS-SECTION (CENTERLINE IS THE MIRROR LINE).



(G) KEY PERMITS DISPLAY OF CONSTANT TEMPERATURE CONTOURS.



CONSTANT TEMPERATURE CONTOURS
OVER COMPLETELY MIRRORED NOZZLE.



SHAFT TORSION EXAMPLE

$$\frac{\partial^2 \phi}{\partial X^2} + \frac{\partial^2 \phi}{\partial Y^2} = -2$$

Consider the torsion of a 1 inch diameter shaft cut by two diametrically opposed identical key ways. The symmetry of this prismatic bar permits the investigation of only one quadrant. The cross-section was enlarged by a factor of 10 (no effect on results) and all dimensions (X,Y values) are in terms of these magnified units. The governing equation is shown above and the boundary condition is $\phi = 0$.

IBM FORTRAN Coding Form

GX28-7327-6 U/M 050** Printed in U.S.A.

PROGRAM: QUADRANT ØF 2-KEYWAY SHAFT DATA

PROGRAMMER: CLYDE-TEK, TØRSIØN PRØBLEM

PUNCHING INSTRUCTIONS — GRAPHIC / PUNCH — PAGE OF — CARD ELECTRO NUMBER*

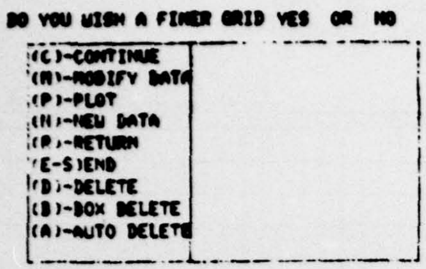
STATEMENT NUMBER | CONT. | FORTRAN STATEMENT | IDENTIFICATION SEQUENCE

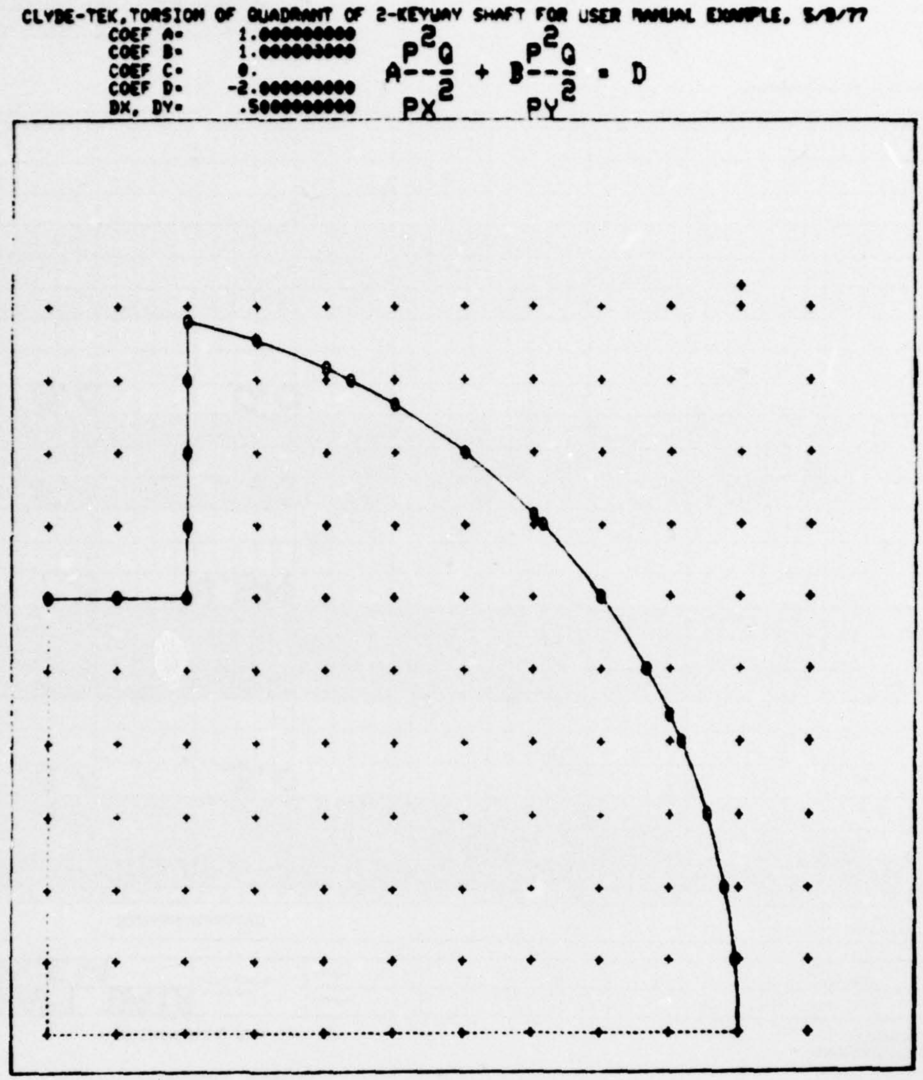
```
CLYDE-TEK [illegible] OF 2-KEYWAY SHAFT FOR USER [illegible] EXAMPLE, 5/19/77
     5 [illegible]                  1.0          1.0              0.0         2.0

  1 ML         0.0          0.0          0.0          3.0
        0.0          0.0

  2 SL  [illegible]         [illegible]  1.0          [illegible]
        [illegible]  [illegible]

  3 SL         1.0          3.0          1.0          4.899
        0.0          0.0

  4 CA         1.0          4.899        5.0          0.0          0.0          0.0  CW
        0.0          0.0

  5 ML         5.0          0.0          0.0          0.0
        0.0          0.0
```

*A standard card form, IBM electro 888157, is available for punching statements from this form

**Number of forms per pad may vary slightly

PUNCH CARD INPUT FOR CLYDE-TEK RUN OF QUADRANT OF 2-KEYWAY SHAFT.





QUADRANT OF SHAFT WITH OVERLAY OF GRID NODES.

DO YOU WISH A FINER GRID YES OR NO
YES

(C)-CONTINUE
(M)-MODIFY DATA
(P)-PLOT
(N)-NEW DATA
(R)-RETURN
(E-S)END
(D)-DELETE
(B)-BOX DELETE
(A)-AUTO DELETE

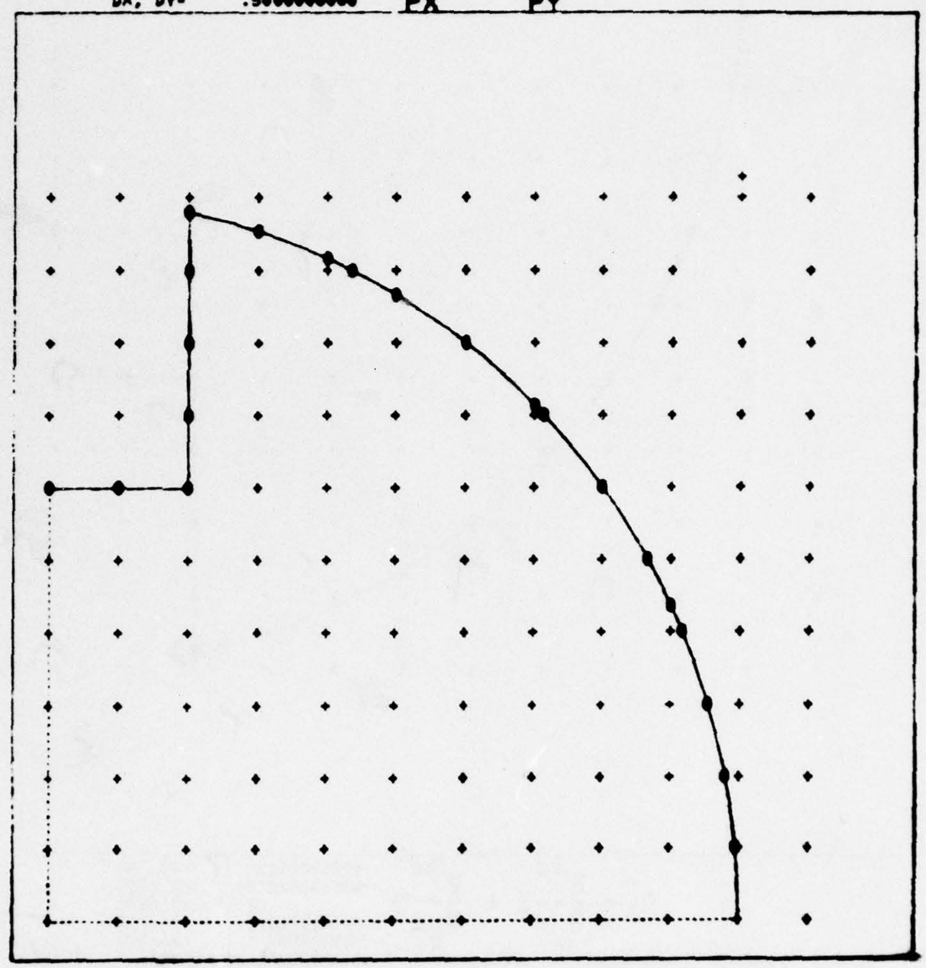
(1)-DONE (2)-KEEP (3) CANCEL

PICK TWO NODES THAT FORM A DIAGONAL OF THE AREA TO BE MADE FINER

CLYDE-TEK,TORSION OF QUADRANT OF 2-KEYWAY SHAFT FOR USER MANUAL EXAMPLE, 8/9/77

COEF A=	1.000000000
COEF B=	1.000000000
COEF C=	0.
COEF D=	-2.000000000
DX, DY=	.5000000000

$$A\frac{\partial^2 Q}{\partial X^2} + B\frac{\partial^2 Q}{\partial Y^2} = D$$



FOR FINER GRID, INPUT "YES"
AND PICK CORNERS.

DO YOU WISH A FINER GRID YES OR NO
YES

(C)-CONTINUE
(M)-MODIFY DATA
(P)-PLOT
(N)-NEW DATA
(R)-RETURN
(E-S)END
(D)-DELETE
(B)-BOX DELETE
(A)-AUTO DELETE

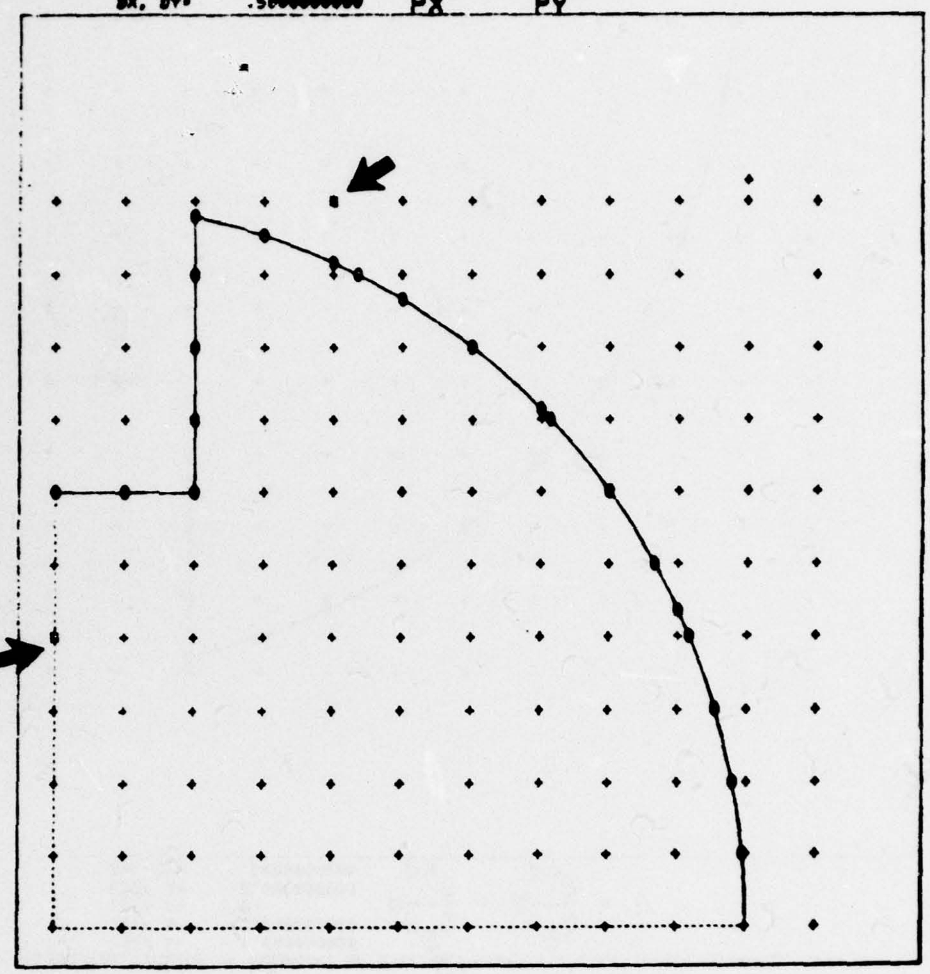
(1)-DONE (2)-KEEP (3) CANCEL

PICK TWO NODES THAT FORM A DIAGONAL
OF THE AREA TO BE MADE FINER
TWO NODES HAVE BEEN PICKED.
KEEP OR CANCEL

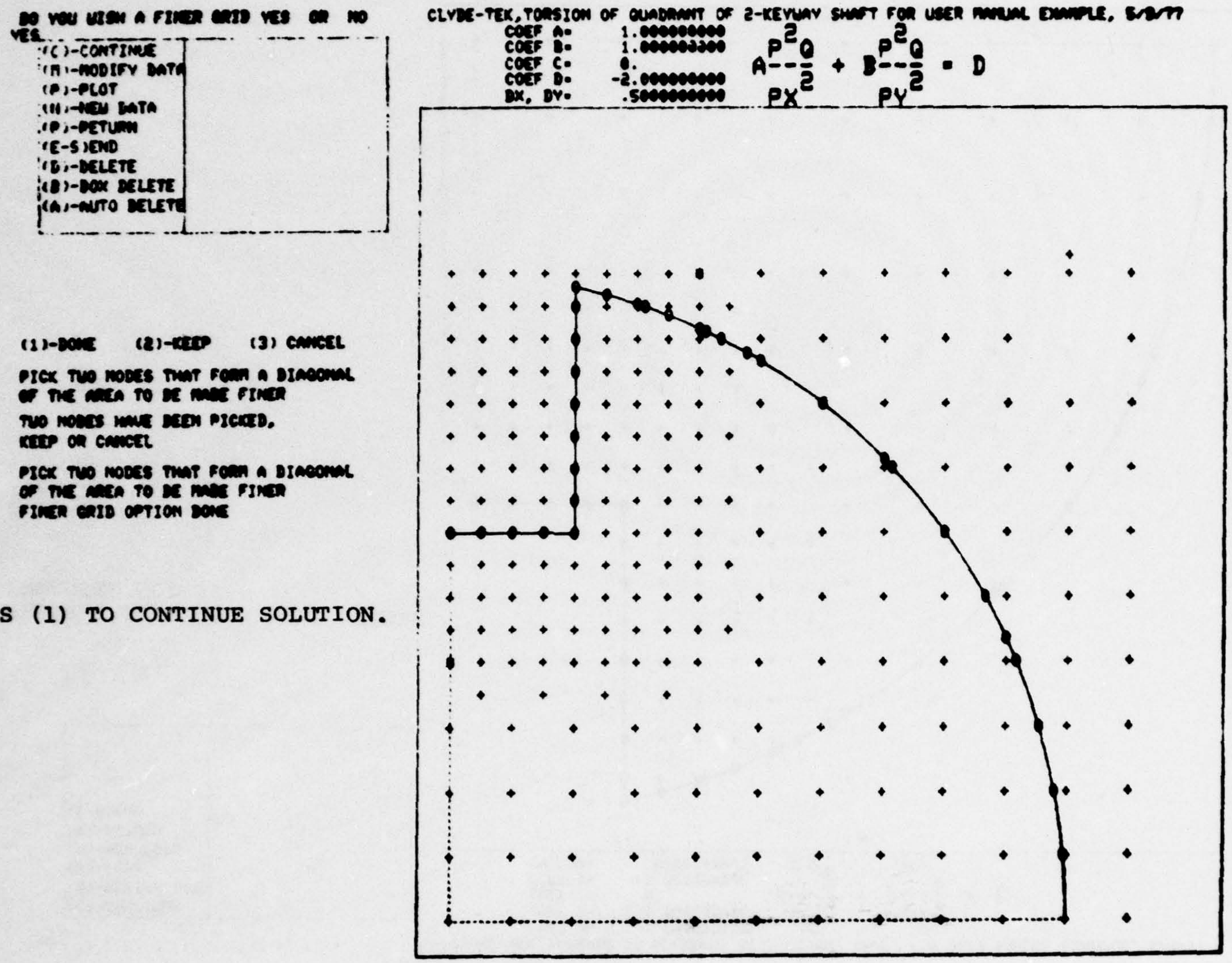
CLYDE-TEK,TORSION OF QUADRANT OF 2-KEYWAY SHAFT FOR USER MANUAL EXAMPLE, 5/8/77

COEF A= 1.000000000
COEF B= 1.000000000
COEF C= 0.
COEF D= -2.000000000
DX, DY= .5000000000

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



DEPRESS (2) KEY TO VERIFY CORNERS.



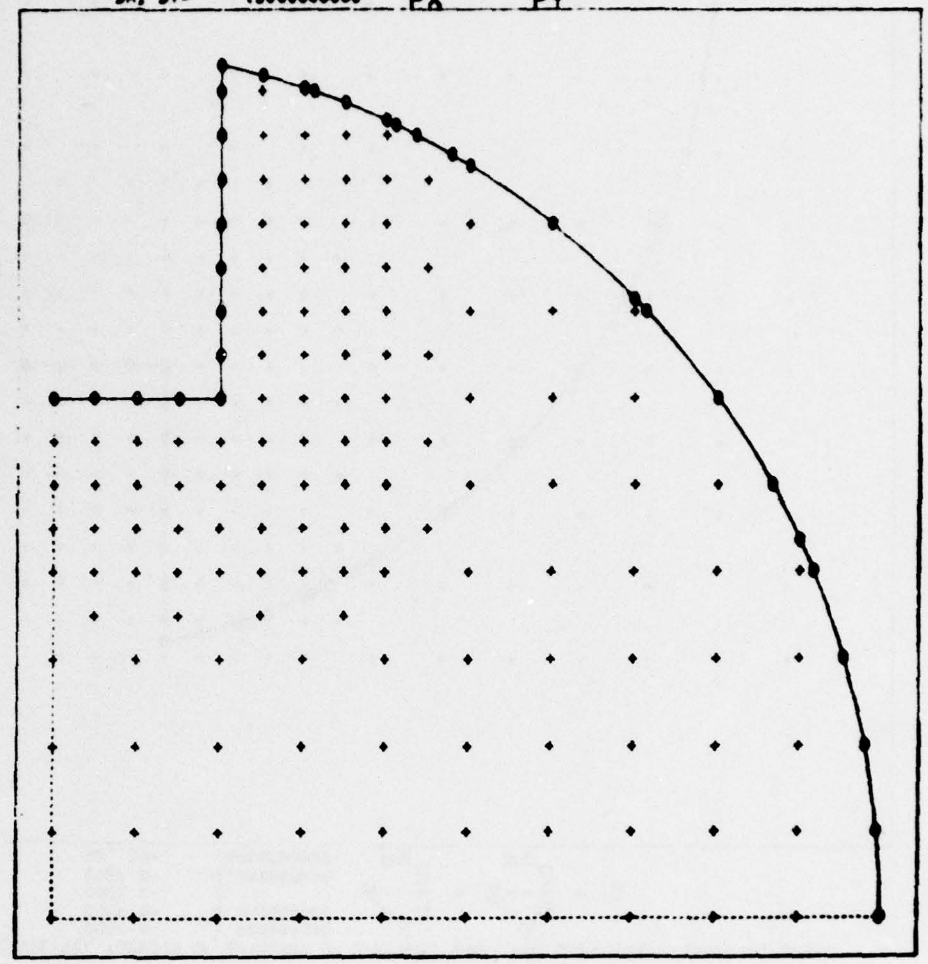
DEPRESS (1) TO CONTINUE SOLUTION.

CLVGR-TEK, TORSION OF QUADRANT OF 2-KEYWAY SHAFT FOR USER MANUAL EXAMPLE, 5/9/77

COEF A=	1.000000000
COEF B=	1.000000000
COEF C=	0.
COEF D=	-2.000000000
DX, DY=	.5000000000

$$A\frac{\partial^2 Q}{\partial X^2} + B\frac{\partial^2 Q}{\partial Y^2} = D$$

(C)-CONTINUE
(M)-MODIFY DATA
(P)-PLOT
(N)-NEW DATA
(R)-RETURN
(E-S)END

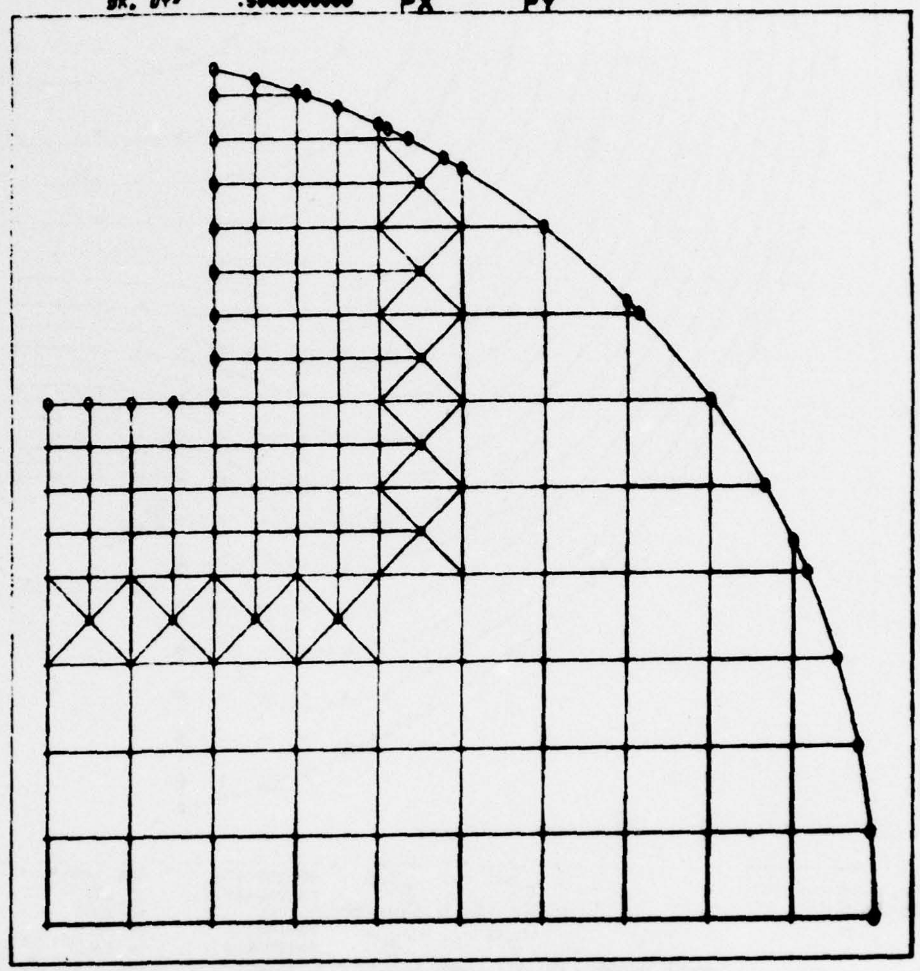


DEPRESS (A) KEY FOR AUTO DELETE
OF UNWANTED NODES.

```
CLYDE-TEK,TORSION OF QUADRANT OF 2-KEYWAY SHAFT FOR USER MANUAL EXAMPLE, 5/9/77
         COEF A=       1.000000000
         COEF B=       1.000000000
         COEF C=       0.
         COEF D=      -2.000000000
         DX, DY=       .5000000000
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$

```
(C)-CONTINUE
(M)-MODIFY DATA
(P)-PLOT
(N)-NEW DATA
(R)-RETURN
(E-S)END
```



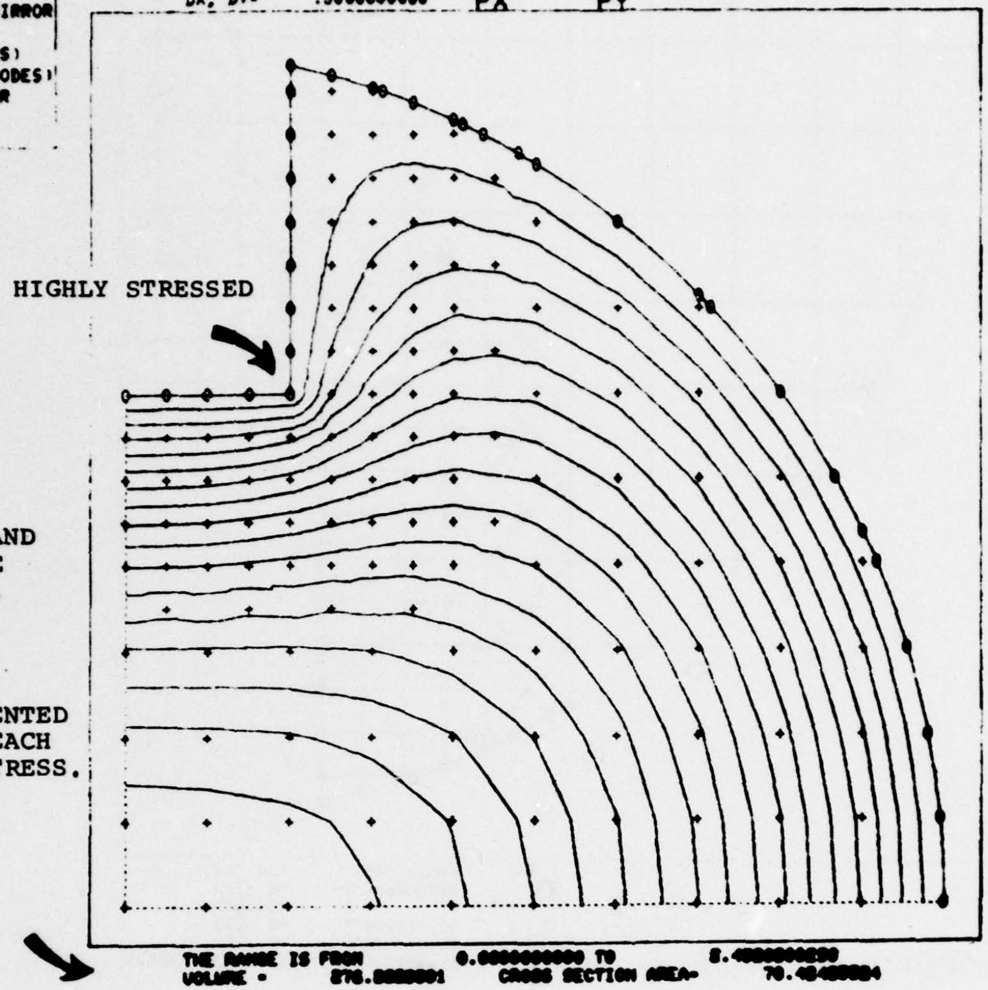
DEPRESS (C) KEY FOR DISPLAY OF ACTUAL FINITE DIFFERENCE GRID.

CLYDE-TEK, TORSION OF QUADRANT OF 2-KEYWAY SHAFT FOR USER MANUAL EXAMPL

```
COEF A=    1.000000000
COEF B=    1.000000000
COEF C=    0.
COEF D=   -2.000000000
DX, DY=    .5000000000
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$

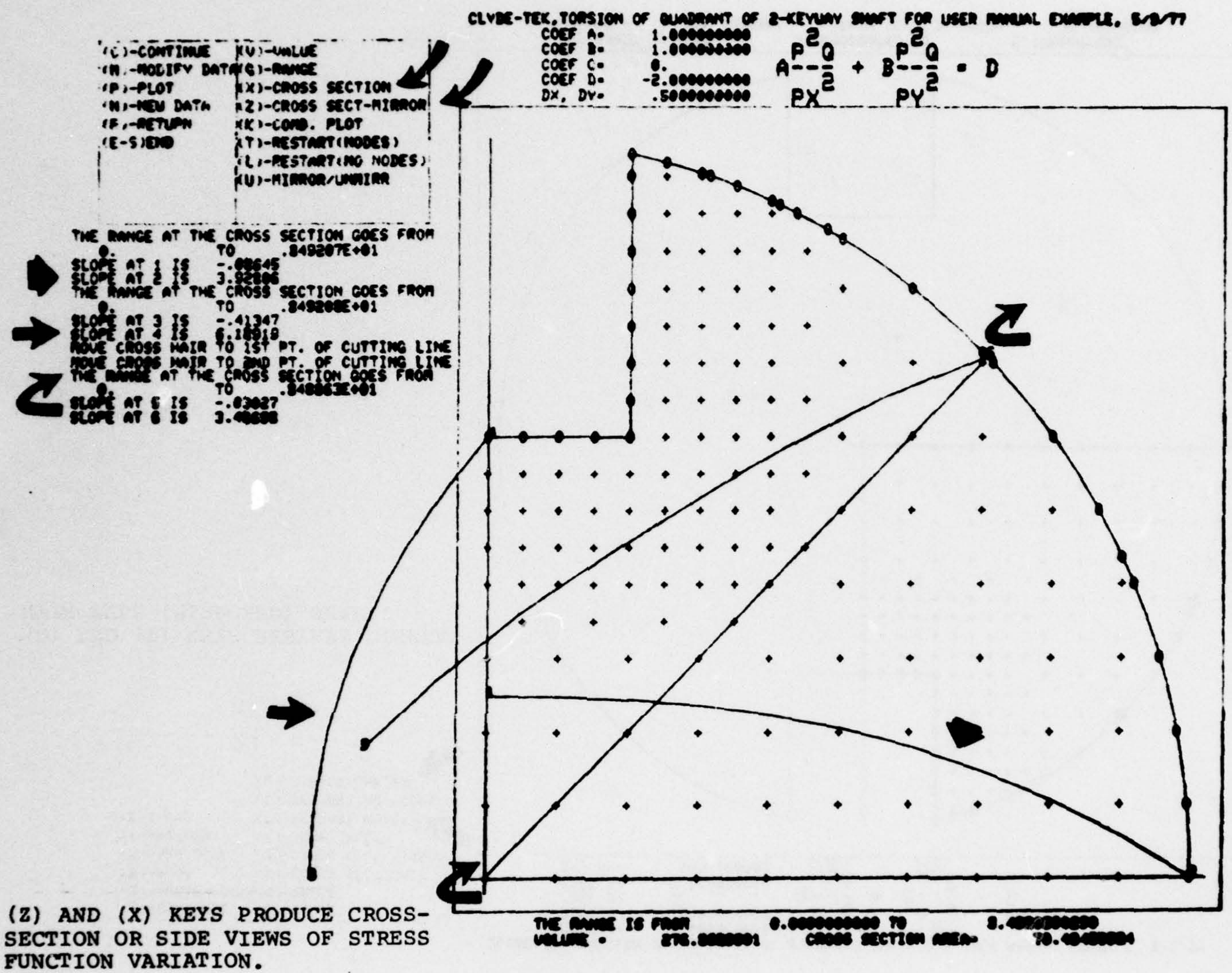
```
(C)-CONTINUE       (V)-VALUE
(M)-MODIFY DATA    (G)-RANGE
(P)-PLOT           (X)-CROSS SECTION
(N)-NEW DATA       (Z)-CROSS SECT-MIRROR
(B)-RETURN         (K)-COMB. PLOT
(E-S)END           (T)-RESTART(NODES)
                   (L)-RESTART(NO NODES)
                   (U)-MIRROR/UNMIRR

ENTER MINIMUM = .5
ENTER MAXIMUM = 8.
ENTER NO. OF CONTOURS= 016
016
                   .50000000E+00
                   .10000000E+01
                   .15000000E+01
```



THE RANGE IS FROM 0.0000000000 TO 8.4000000250
VOLUME = 276.0000001 CROSS SECTION AREA= 70.40400004

DEPRESS (C) FOR SOLUTION, AND (G) KEY FOR DISPLAY OF RANGE OF STRESS FUNCTION CONTOURS.

THE CLOSER THE EQUALLY INCREMENTED STRESS FUNCTION PLOTS ARE TO EACH OTHER, THE HIGHER THE SHEAR STRESS.



(Z) AND (X) KEYS PRODUCE CROSS-SECTION OR SIDE VIEWS OF STRESS FUNCTION VARIATION.

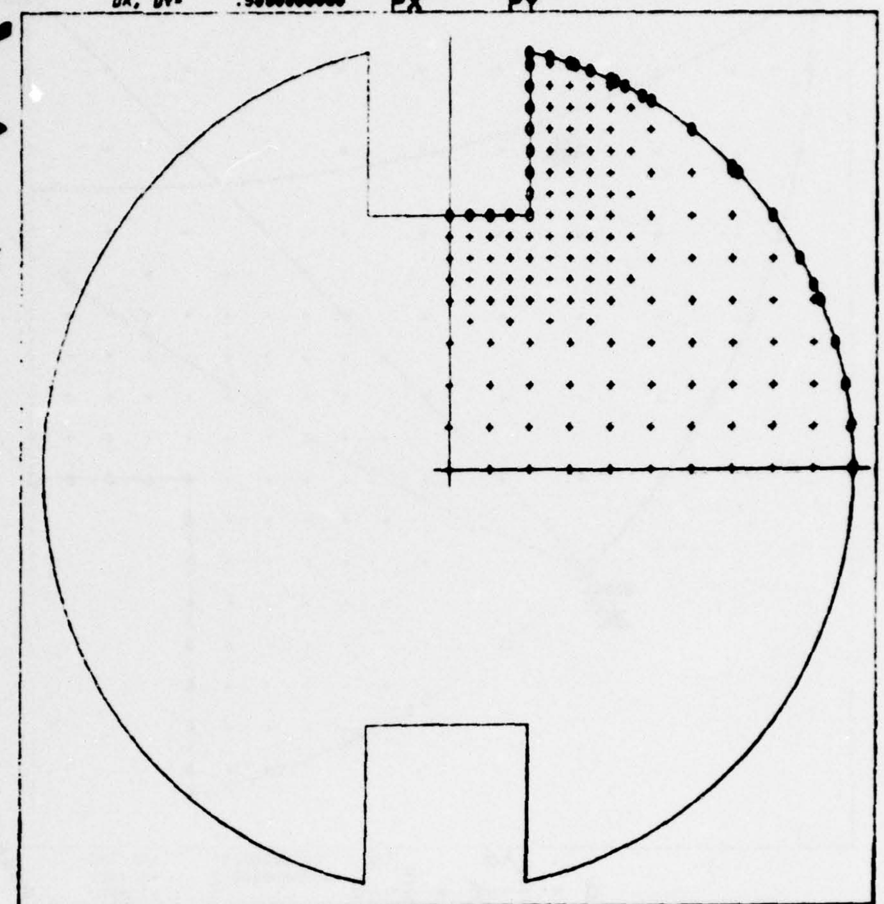
(C)-CONTINUE	(V)-VALUE
(M)-MODIFY DATA	(G)-RANGE
(P)-PLOT	(X)-CROSS SECTION
(N)-NEW DATA	(Z)-CROSS SECT-MIRROR
(R)-RETURN	(K)-COND. PLOT
(E-S)END	(T)-RESTART(NODES)
	(L)-RESTART(NO NODES)
	(U)-MIRROR/UNMIRR

(U) AND (T) KEYS RESTART DISPLAY WITH FULL (MIRRORED) SHAFT.

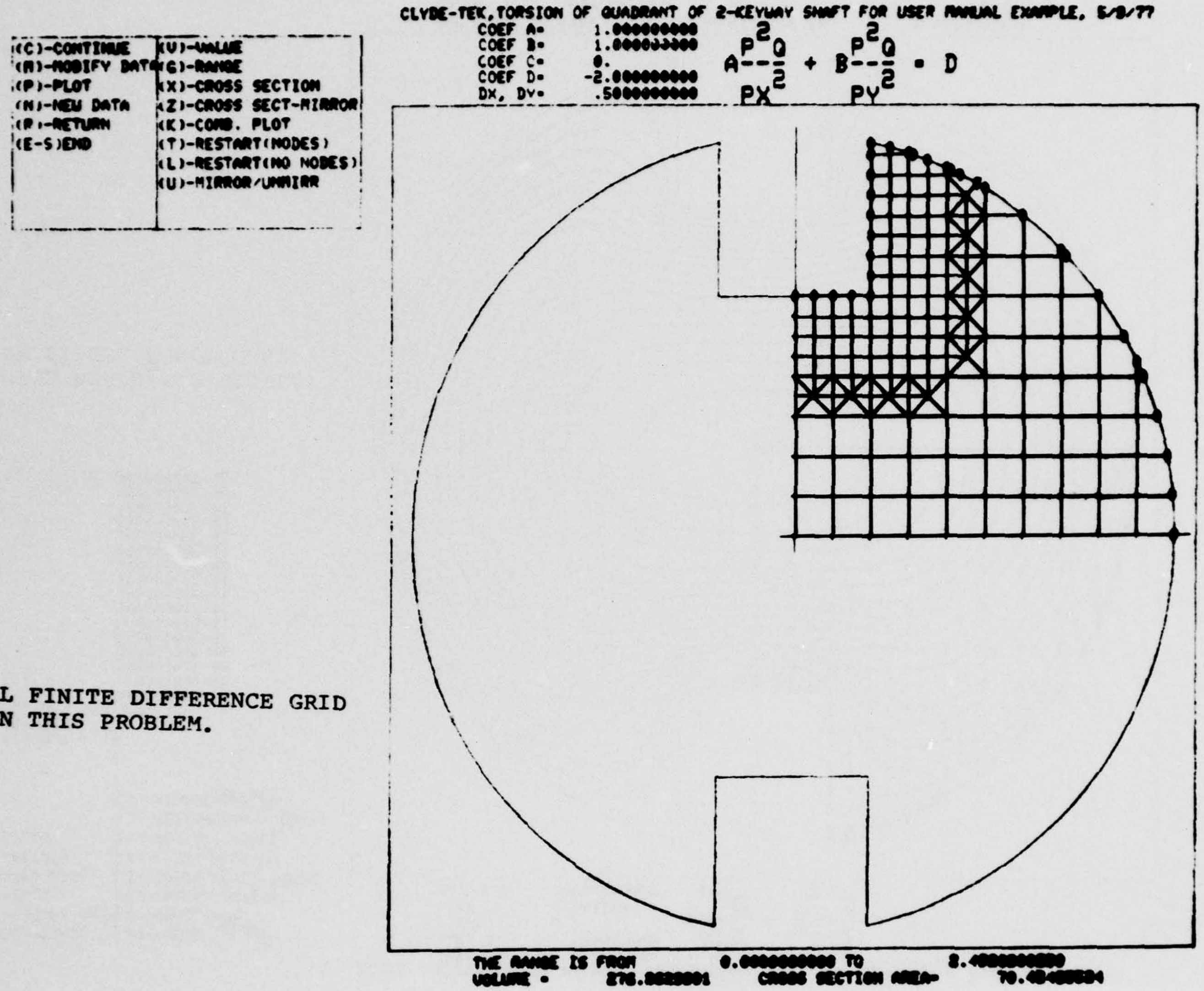
CLYDE-TEK,TORSION OF QUADRANT OF 2-KEYWAY SHAFT FOR USER MANUAL EXAMPLE, 5/9/77

COEF A= 1.000000000
COEF B= 1.000000000
COEF C= 0.
COEF D= -2.000000000
DX, DY= .500000000

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



THE RANGE IS FROM 0.0000000000 TO 8.4000000000
VOLUME = 276.8620001 CROSS SECTION AREA= 70.48400004



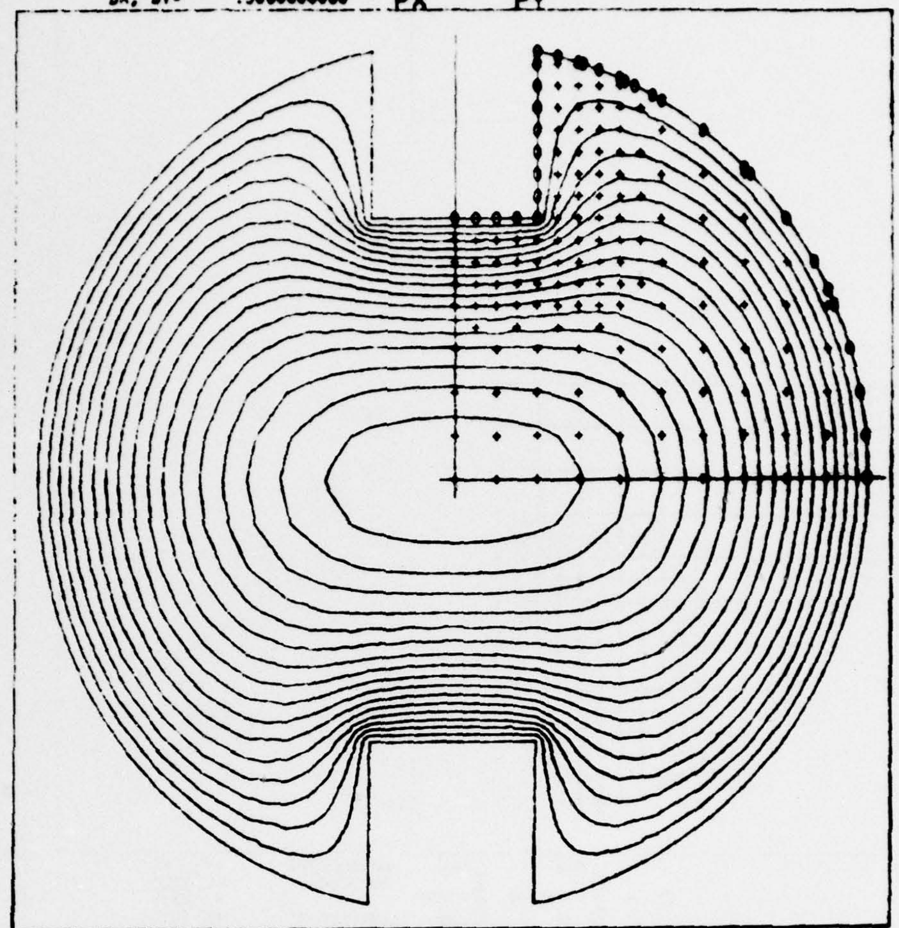
ACTUAL FINITE DIFFERENCE GRID
USED IN THIS PROBLEM.

```
(C)-CONTINUE      (V)-VALUE
(M)-MODIFY DATA   (G)-RANGE
(P)-PLOT          (X)-CROSS SECTION
(N)-NEW DATA      (Z)-CROSS SECT-MIRROR
(R)-RETURN        (K)-COMB. PLOT
(E-S)END          (T)-RESTART(NODES)
                  (L)-RESTART(NO NODES)
                  (U)-MIRROR/UNMIRR

ENTER MINIMUM = .5
ENTER MAXIMUM = 8.
ENTER NO. OF CONTOURS= 016
016
                  .5[illegible]E+00
                  .1[illegible]E+01
                  .15[illegible]E+01
                  .2[illegible]+01
                  .25[illegible]+01
                  .3[illegible]+01
                  .35[illegible]+01
                  .4[illegible]+01
                  .45[illegible]+01
                  .5[illegible]+01
                  .55[illegible]+01
                  .6[illegible]+01
                  .65[illegible]+01
                  .7[illegible]+01
                  .75[illegible]+01
                  .8[illegible]+01
```

CLYDE-TEK,TORSION OF QUADRANT OF 2-KEYWAY SHAFT FOR USER MANUAL EXAMPLE, 5/9/77

```
COEF A=    1.000000000
COEF B=    1.000000000
COEF C=    0.
COEF D=   -2.000000000
DX, DY=    .5000000000
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



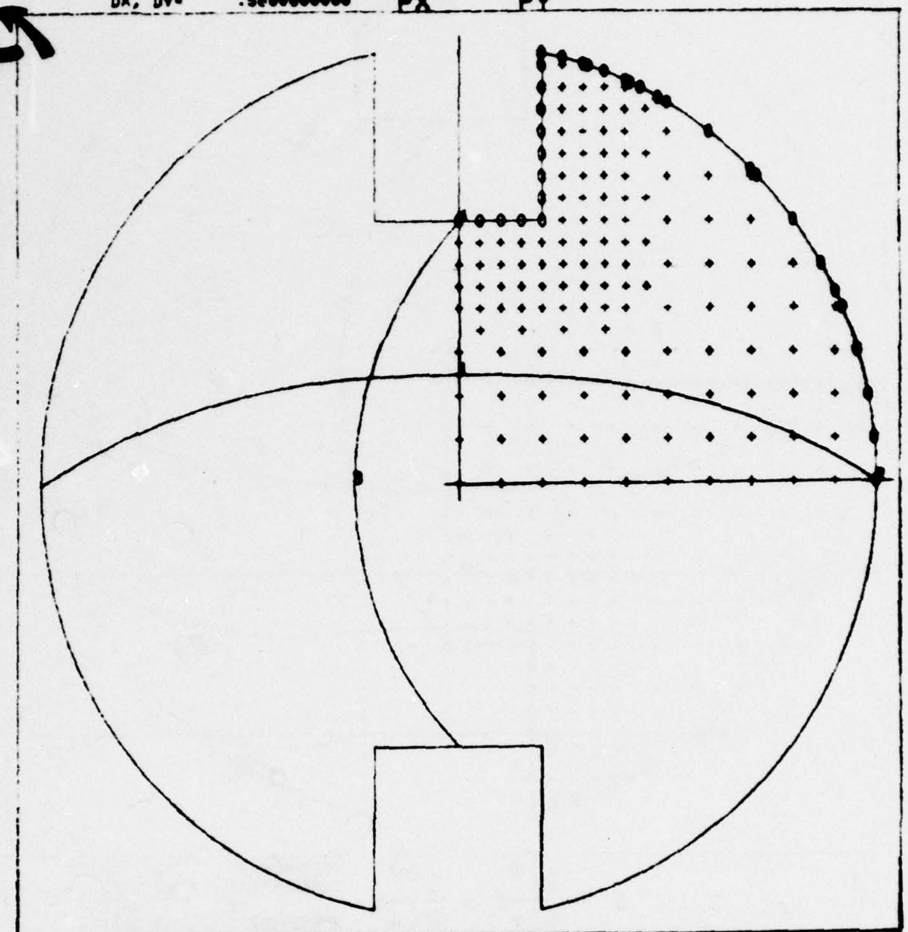
```
THE RANGE IS FROM      0.0000000000 TO      8.4[illegible]
VOLUME =      276.8[illegible]    CROSS SECTION AREA=      78.4[illegible]
```

(G) KEY USED AGAIN FOR DISPLAY
OF RANGE OF STRESS FUNCTIONS.

```
(C)-CONTINUE        (V)-VALUE
(M)-MODIFY DATA     (G)-RANGE
(P)-PLOT            (X)-CROSS SECTION
(N)-NEW DATA        (Z)-CROSS SECT-MIRROR
(R)-RETURN          (K)-COMB. PLOT
(E-S)END            (T)-RESTART(NODES)
                    (L)-RESTART(NO NODES)
                    (U)-MIRROR/UNMIRR

THE RANGE AT THE CROSS SECTION GOES FROM
   0.               TO     .849207E+01
SLOPE AT 1 IS     -.[illegible]645
SLOPE AT 2 IS     3.[illegible]
THE RANGE AT THE CROSS SECTION GOES FROM
   0.               TO     .84920[illegible]E+01
SLOPE AT 3 IS     -.41347
SLOPE AT 4 IS     6.18919
```

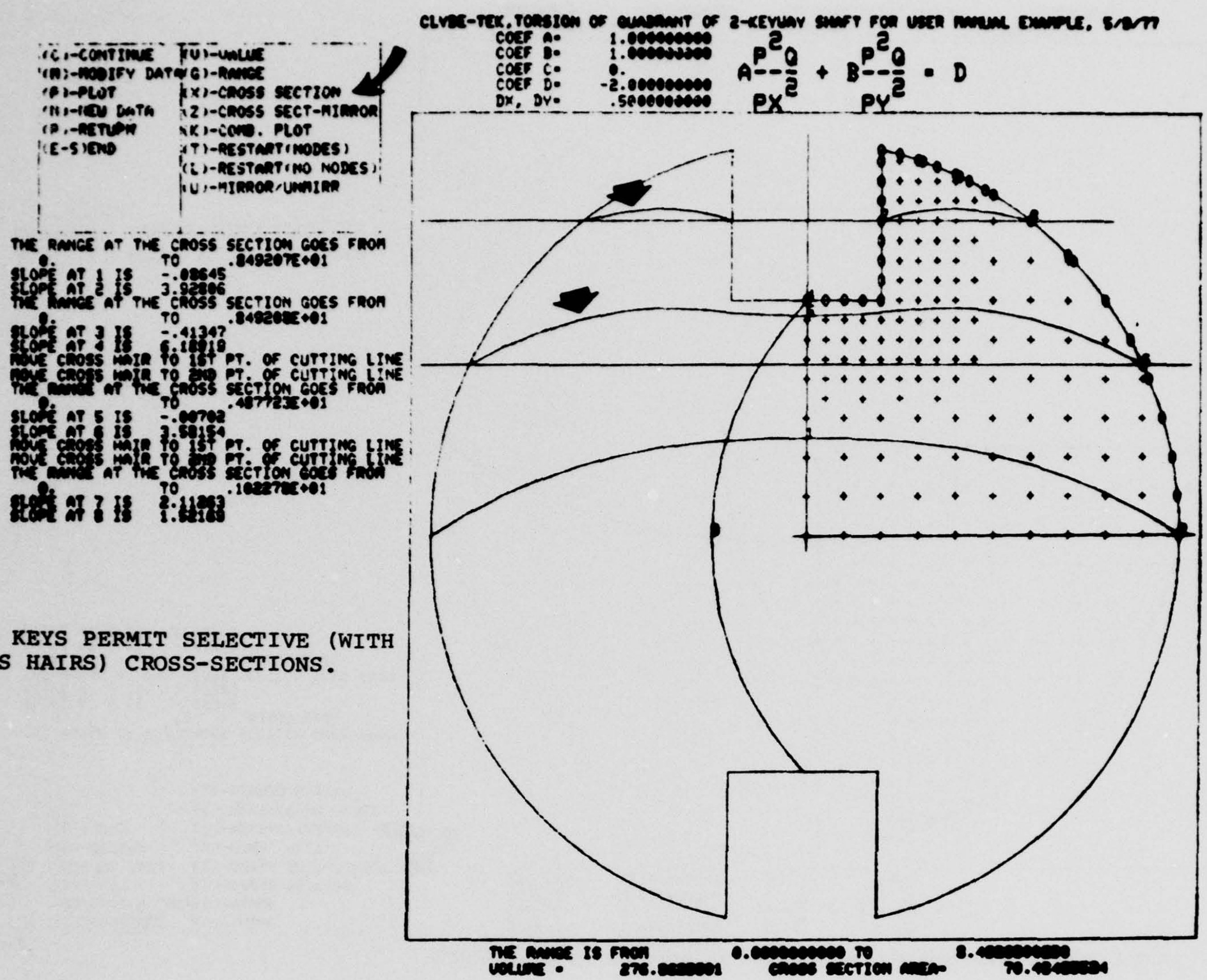
```
CLYDE-TEK,TORSION OF QUADRANT OF 2-KEYWAY SHAFT FOR USER MANUAL EXAMPLE, 5/8/77
     COEF A=     1.000000000
     COEF B=     1.000000000
     COEF C=     0.
     COEF D=     -2.000000000
     DX, DY=     .5000000000
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



```
THE RANGE IS FROM      0.0000000000 TO      8.4[illegible]
VOLUME =     276.[illegible]1     CROSS SECTION AREA=     70.4[illegible]
```

(T) AND (Z) KEYS CLEAR SCREEN, AND DISPLAY CROSS-SECTIONS AT MIRROR LINES.



(X) KEYS PERMIT SELECTIVE (WITH CROSS HAIRS) CROSS-SECTIONS.

```
(C)-CONTINUE      (V)-VALUE
(M)-MODIFY DATA   (G)-RANGE
(P)-PLOT          (X)-CROSS SECTION
(N)-NEW DATA      (Z)-CROSS SECT-MIRROR
(R)-RETURN        (K)-COMB. PLOT
(E-S)END          (T)-RESTART(NODES)
                  (L)-RESTART(NO NODES)
                  (U)-MIRROR/UNMIRR

MOVE CROSS HAIR TO 1ST PT. OF CUTTING LINE
MOVE CROSS HAIR TO 2ND PT. OF CUTTING LINE
THE RANGE AT THE CROSS SECTION GOES FROM
  0.             TO     .848803E+01
SLOPE AT 1 IS    -.03376
SLOPE AT 2 IS    3.45689
MOVE CROSS HAIR TO 1ST PT. OF CUTTING LINE
MOVE CROSS HAIR TO 2ND PT. OF CUTTING LINE
THE RANGE AT THE CROSS SECTION GOES FROM
  0.             TO     .739452E+01
SLOPE AT 3 IS    -.00344
SLOPE AT 4 IS    2.03901
```

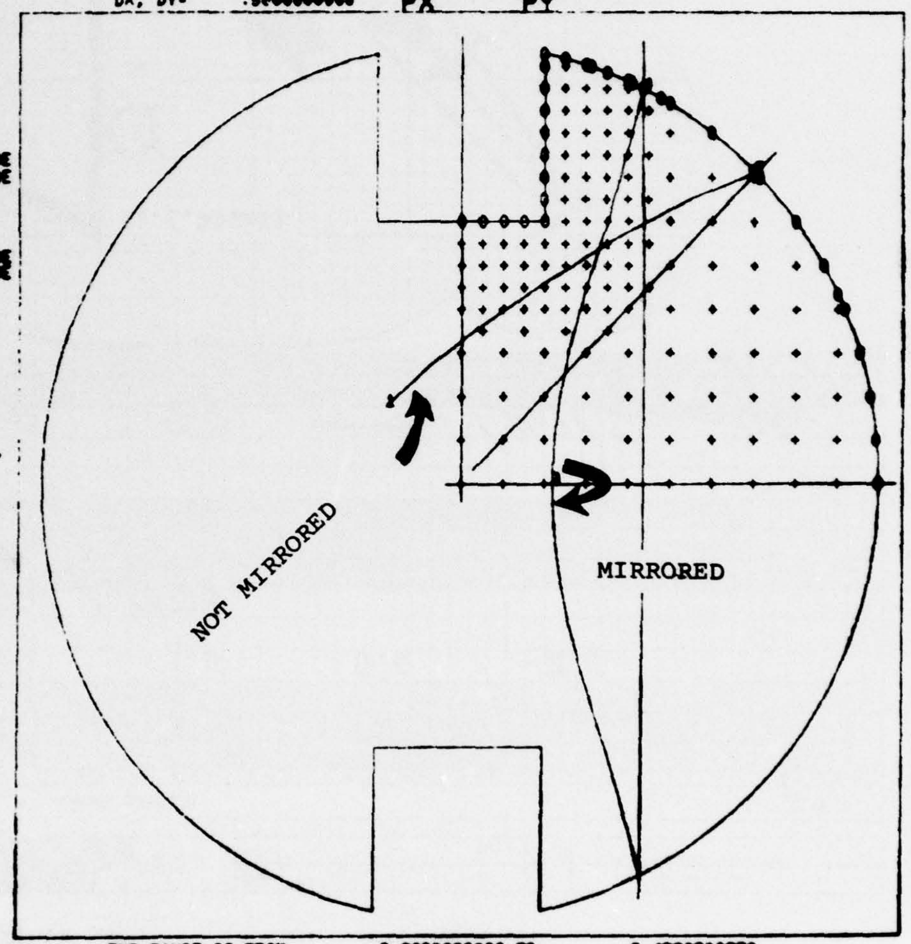
(T) AND (X) KEYS CLEAR SCREEN,
AND DISPLAY MORE CROSS-SECTIONS.

CROSS-SECTIONS ARE MIRRORED ONLY
IF THE CUTTING PLANE IS NORMAL
TO A MIRROR LINE.

CLYDE-TEK,TORSION OF QUADRANT OF 2-KEYWAY SHAFT FOR USER MANUAL EXAMPLE, 5/9/77

COEF A=	1.000000000	
COEF B=	1.000000000	
COEF C=	0.	
COEF D=	-2.000000000	
DX, DY=	.5000000000	

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



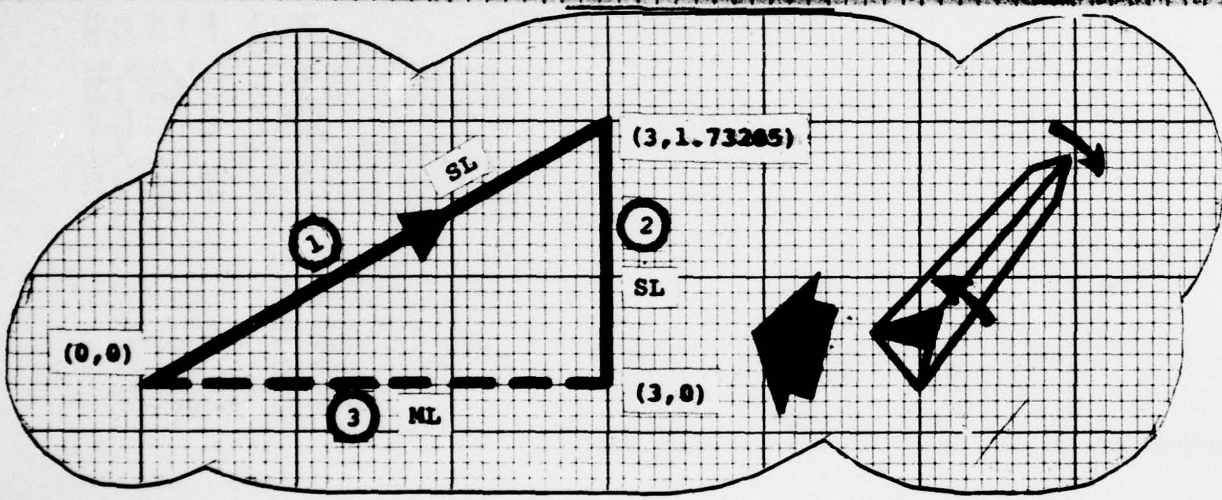
THE RANGE IS FROM 0.0000000000 TO 8.4800000000
VOLUME = 276.8888881 CROSS SECTION AREA= 70.4848584

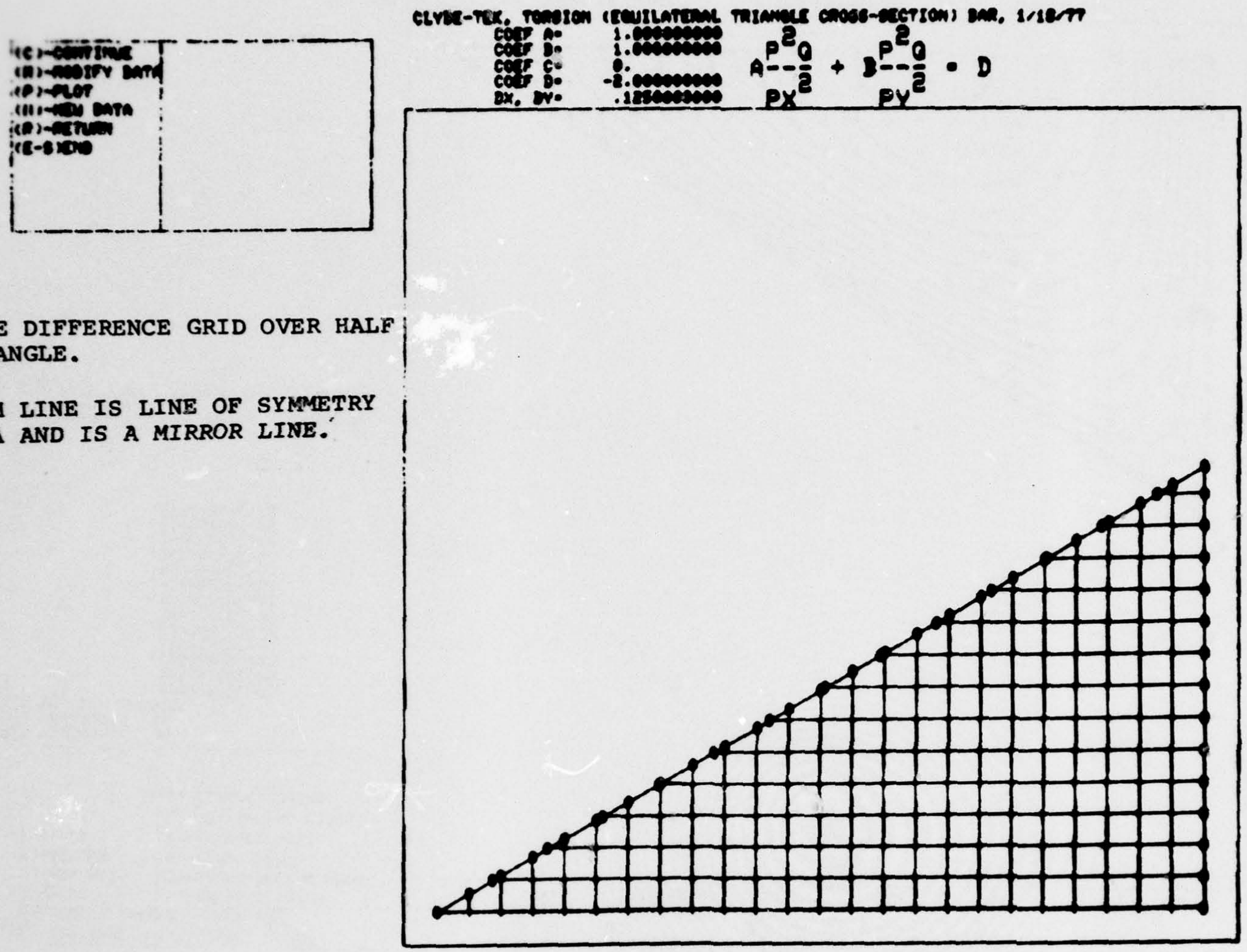
PUNCH CARD INPUT FOR TORSION
OF TRIANGULAR BAR.

PROGRAM: TORSION OF BAR WITH EQUILATERAL
PROGRAMMER: TRIANGLE CROSS-SECTION, DATE: CLYDE-TEK

PUNCHING INSTRUCTIONS | GRAPHIC | PUNCH | PAGE OF | CARD ELECTRO NUMBER

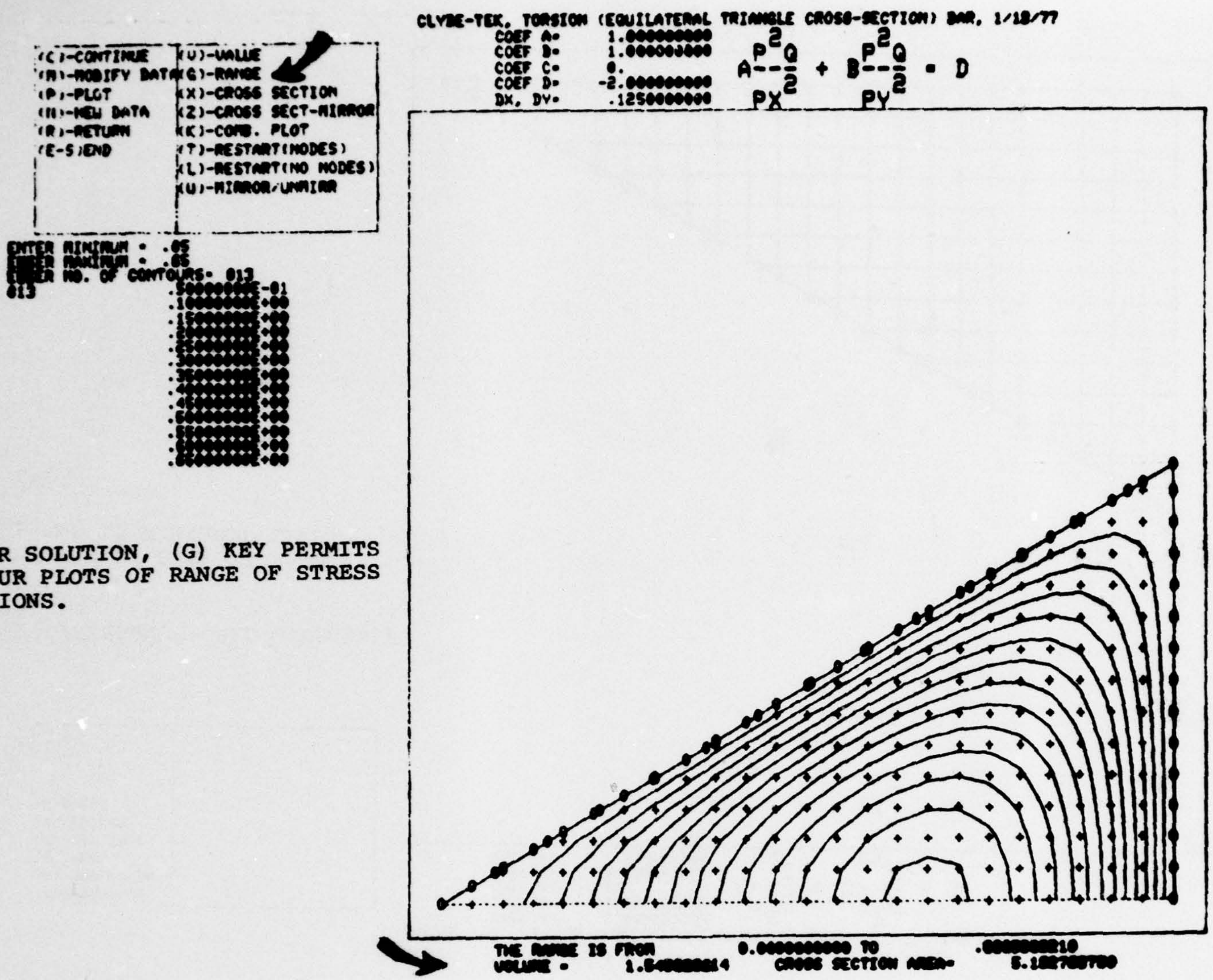
STATEMENT NUMBER	FORTRAN STATEMENT						IDENTIFICATION SEQUENCE
[illegible]			TRIANGLE [illegible]			, 1/18/77	
3	0.125	0.125	1.0	1.0	0.0	-2.0	
1 SL	0.0	0.0	3.0	1.73205			
	0.0	0.0					
2 SL	3.0	1.73205	[illegible]	[illegible]			
	0.0	0.0					
3 ML	3.0	0.0	0.0	0.0	← (Half Symmetry)		
	0.0	0.0					



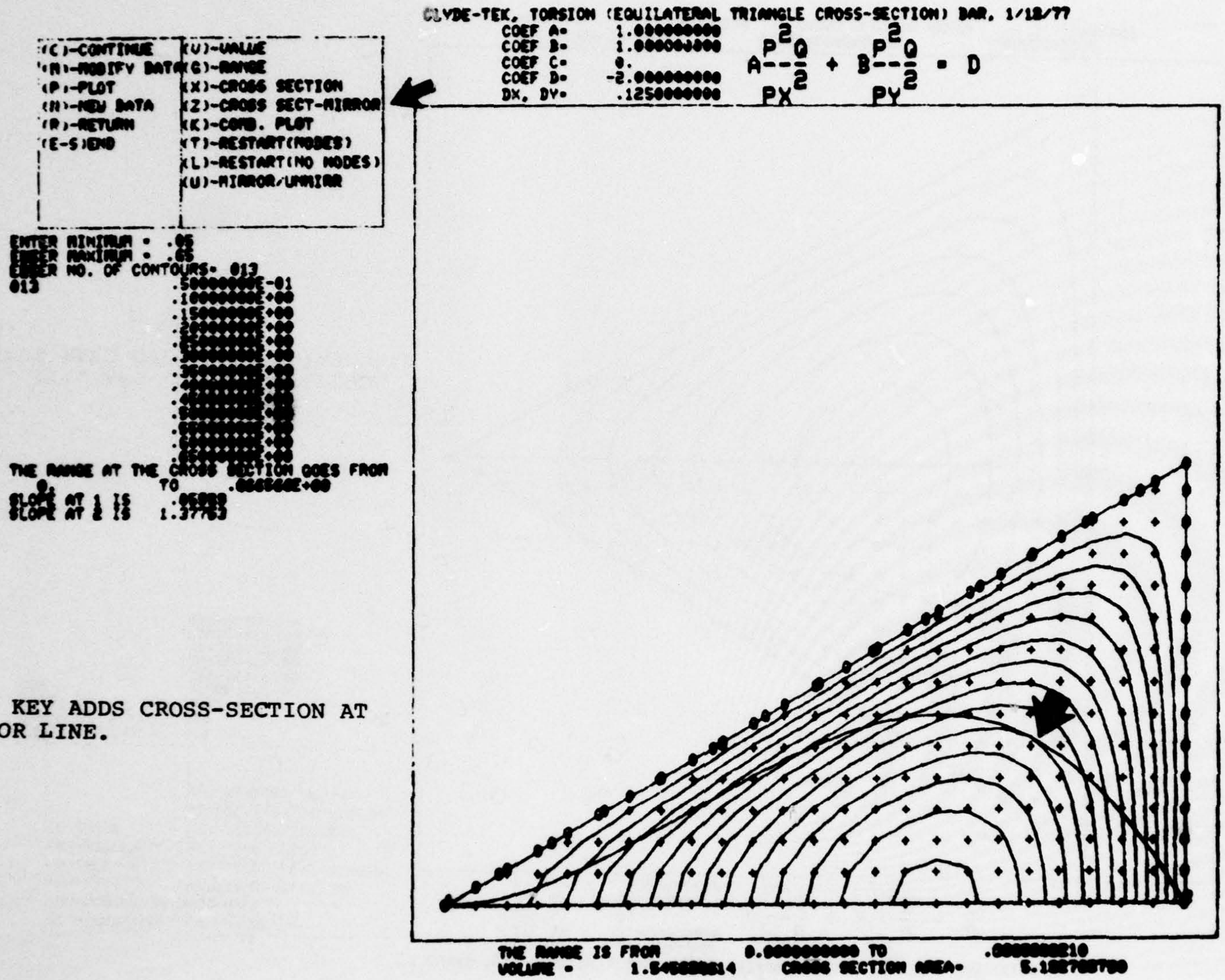


FINITE DIFFERENCE GRID OVER HALF OF TRIANGLE.

BOTTOM LINE IS LINE OF SYMMETRY OF AREA AND IS A MIRROR LINE.



AFTER SOLUTION, (G) KEY PERMITS CONTOUR PLOTS OF RANGE OF STRESS FUNCTIONS.

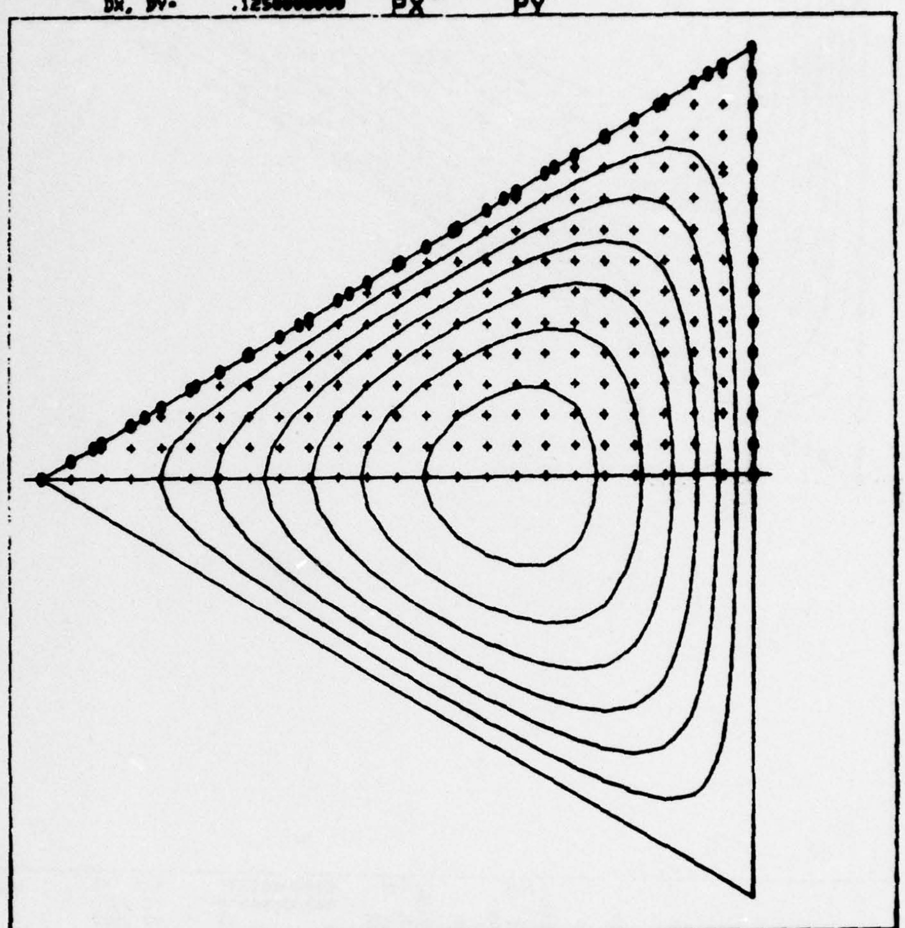


(Z) KEY ADDS CROSS-SECTION AT MIRROR LINE.

```
(C)-CONTINUE          (V)-VALUE
(R)-MODIFY DATA       (G)-RANGE
(P)-PLOT              (X)-CROSS SECTION
(N)-NEW DATA          (Z)-CROSS SECT-MIRROR
(R)-RETURN            (K)-COMB. PLOT
(E-S)END              (T)-RESTART(NODES)
                      (L)-RESTART(NO NODES)
                      (U)-MIRROR/UNMIRR

ENTER MINIMUM : .100
ENTER MAXIMUM : .600
ENTER NO. OF CONTOURS= 006
006
                      .1000000E+00
                      .2000000E+00
                      .3000000E+00
                      .4000000E+00
                      .5000000E+00
                      .6000000E+00
```

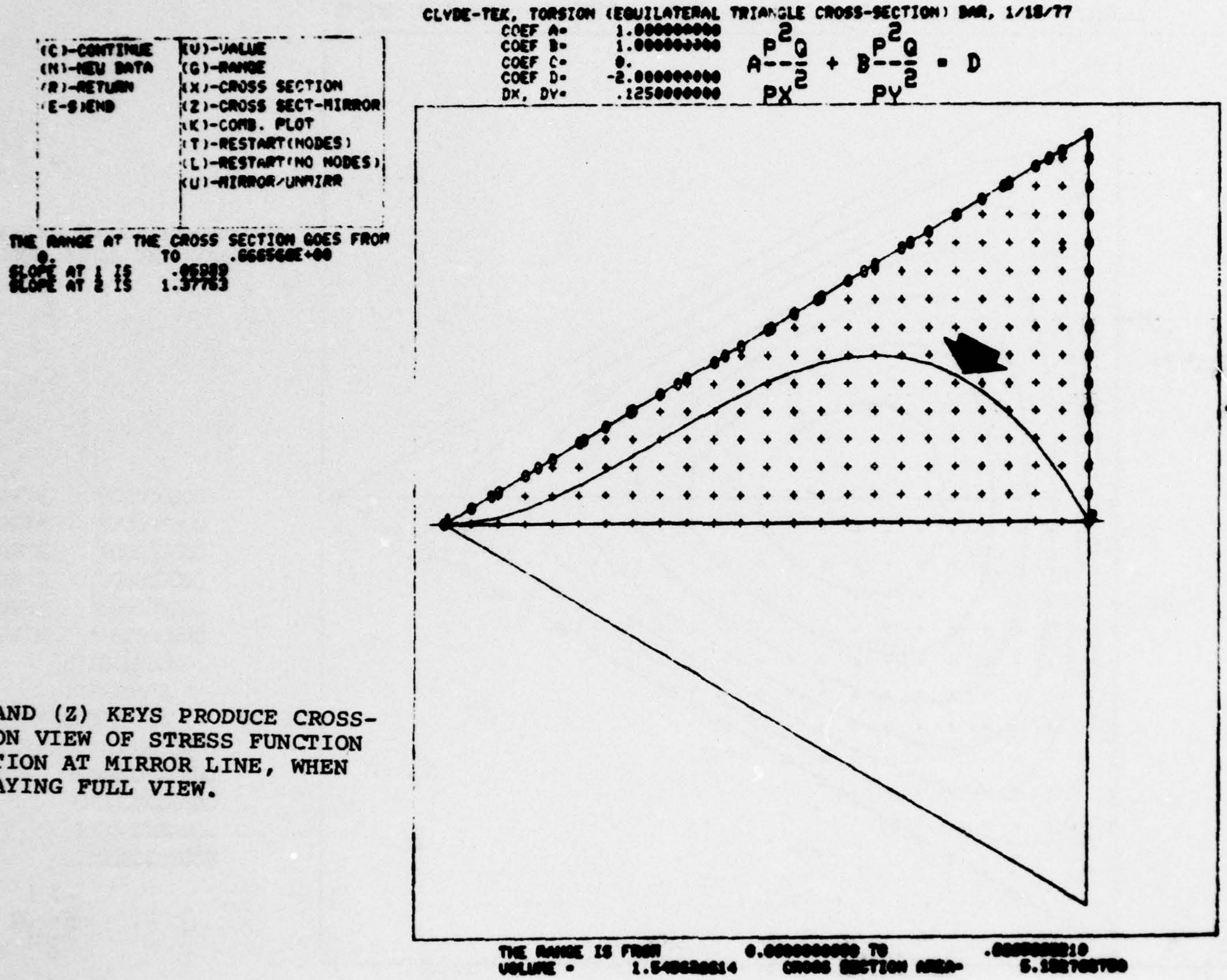
```
CLYDE-TEK, TORSION (EQUILATERAL TRIANGLE CROSS-SECTION) BAR, 1/18/77
      COEF A=     1.000000000
      COEF B=     1.000000000
      COEF C=     0.
      COEF D=    -2.000000000
      DX, DY=     .1250000000
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



```
THE RANGE IS FROM       0.0000000000 TO        .0000000210
VOLUME =      1.5400000014     CROSS SECTION AREA=     5.1000000750
```

(U), (T), AND (G) KEYS PRODUCE CONTOUR MAPS OVER FULL TRIANGULAR AREA.

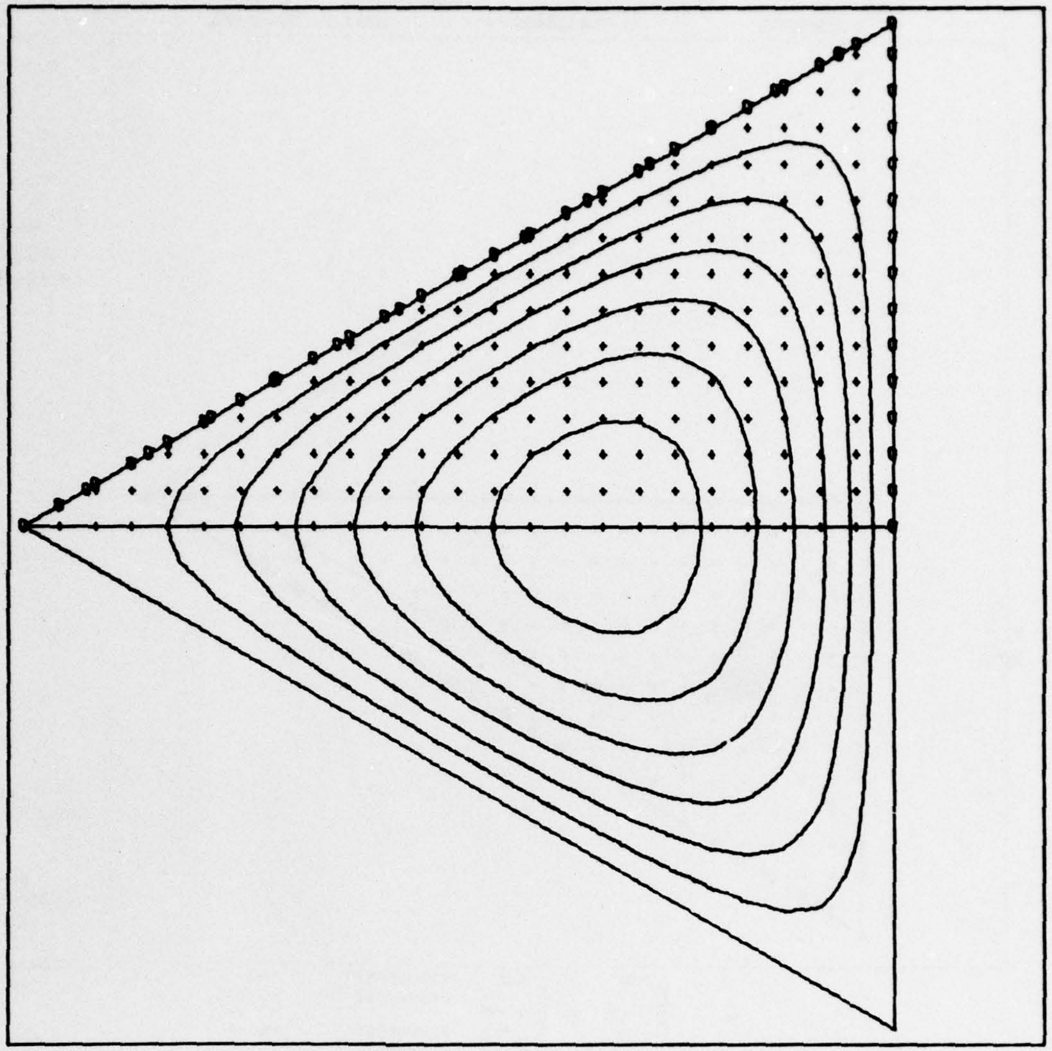


(T) AND (Z) KEYS PRODUCE CROSS-SECTION VIEW OF STRESS FUNCTION VARIATION AT MIRROR LINE, WHEN DISPLAYING FULL VIEW.

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = 0$$

COEF A=	1.0000000000	
COEF B=	1.0000000000	
COEF C=	0.0000000000	
COEF D=	-2.0000000000	
DX,DY =	.1260000000	
RANGE IS	0.000000 TO	.666667
VOLUME =	1.646626614	
AREA =	6.182768760	
CONTOUR VALUE	.100000000	
CONTOUR VALUE	.200000000	
CONTOUR VALUE	.300000000	
CONTOUR VALUE	.400000000	
CONTOUR VALUE	.500000000	
CONTOUR VALUE	.600000000	

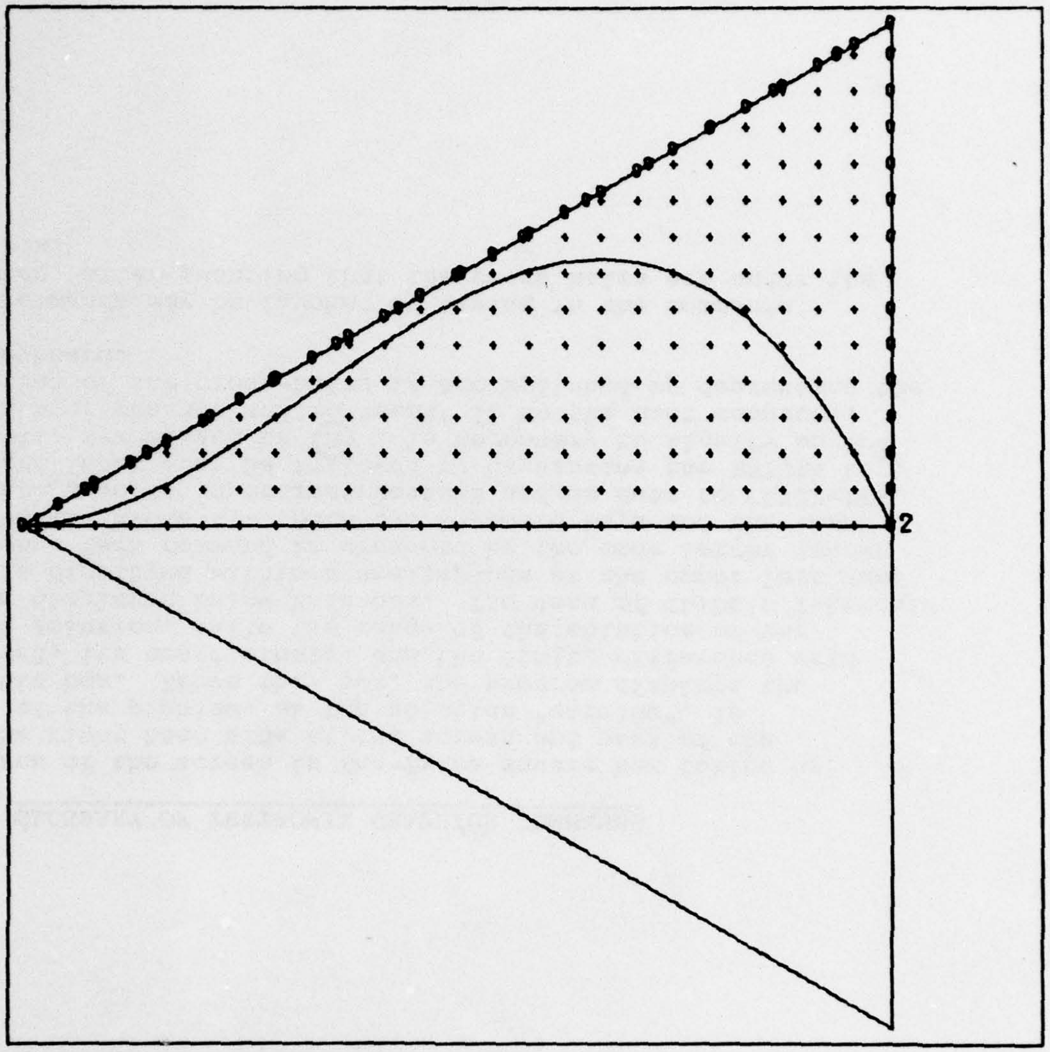
CALCOMP PLOT OF CONTOURS
GENERATED BY CLYDE-BATCH.



CLYDE-TEK, TORSION (EQUILATERAL TRIANGLE CROSS-SECTION) BAR, 1/18/77

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = 0$$

COEF A= 1.0000000000
COEF B= 1.0000000000
COEF C= 0.0000000000
COEF D= -2.0000000000
DX,DY = .1250000000
RANGE IS 0.000000 TO .666667
VOLUME = 1.545626614
AREA = 5.182768750
CROSS SECTION LINE
(0. , .625000E-06 TO
.300000E+01, .625000E-06)
CROSS SECTION RANGE IS
0.000000 TO .666666
SLOPE AT 1 IS .05989
SLOPE AT 2 IS 1.37763



CLYDE-TEK. TORSION (EQUILATERAL TRIANGLE CROSS-SECTION) BAR. 1/18/77

CALCOMP PLOT OF CROSS-SECTION
GENERATED BY CLYDE-BATCH.

GLOSSARY OF TEKTRONIX GRAPHICS COMMANDS

The working area of the screen is the large square box taking up virtually all of the right hand side of the screen and part of the left. The picture of the problem, as the solution "unfolds", is displayed within this box. Above this box, the program displays the equation being solved, its coefficients, and the finite difference grid spacing used in the solution, while the range of the solution of the problem variable is displayed below this box. The menu of CLYDE's Tektronix graphics commands is displayed within a smaller box at the upper left hand portion of the screen. Each command is preceded by the code letter (shown in parentheses) used to invoke it. Both the keyboard keys and the thumb wheel cross-hairs are used to input instructions and/or data to CLYDE-TEK. Alphanumeric keyboard input must be followed by depressing the RETURN key. This RETURN keystroke, symbolized by R, is necessary to signify an end to the string of data or message and to "send" it to the host computer. "Sending" the position of the cross-hairs is accomplished by depressing the space-bar on the keyboard.

The graphics commands may be invoked by keying in the commands' preceding code letter, after ensuring that the cross hairs are under the graphics commands box.

(C) - CONTINUE:	This directs CLYDE to continue along its programmed sequence of solution steps.
(M) - MODIFY DATA:	This command displays the card images* of the data. Data cards or individual words may be changed, deleted, or added. This MODIFY DATA mode is identical to that employed in the PIPS-TEK system. Users are referred to Users Manual UM 76-2, entitled "PIPSTEK".
(P) - PLOT:	Creates a plot file of the current working area display for use by a *CalComp digital* plotter. This is a backup option, for use when the Tektronix hard copier is inoperative.
(N) - NEW DATA:	Returns to the start of the program and will read in the next input data file, if one exists.
(E-S) - END or STOP:	Ends the program run.
(D) - DELETE:	Enables the user to delete individual inner domain nodes, one by one, by selecting each node with the cross-hairs and depressing the space-bar.
(B) - BOX DELETE:	Permits the user to delete an entire rectangle or box of nodes by selecting any two diagonal corner nodes of the rectangular area (one-at-a-time) with the cross-hairs.

*(See example, next page)

PAGE	REPAGE	ROLL UP	ROLL DOWN
MODIFY	REPLACE	ADD	CANCEL
RESTORE	DELETE		FINISH

PICK AN OPTION

NUMBER OF CONTOUR SEGMENTS = 5
DX= .500000 A= 1.00000 B= 1.00000 C= 0. D= -2.00000

TITLE = QUADRANT OF 2-KEYED SHAFT TORSION-SOAP FILM ANALOGY 12/1/71

	LIN OR ARC	CCW OR CW	X-COORD. 1ST POINT / BOUNDARY CONDITION 1ST POINT	Y-COORD. 1ST POINT / BOUNDARY CONDITION FULL SEG.	X-COORD. 2ND POINT	Y-COORD. 2ND POINT	X-COORD. OF CENTER	Y-COORD. OF CENTER
10	LN		0.	0.	0.	3.00000	0.	0.
20			0.	0.				
30	LN		0.	3.00000	1.00000	3.00000	0.	0.
40			0.	0.				
50	LN		1.00000	3.00000	1.00000	4.25000	0.	0.
60			0.	0.				
70	ARC	CCW	1.00000	4.25000	5.00000	0.	-.250000E-0[illegible]	.300000E-0[illegible]
80			0.	0.				
90	LN		5.00000	0.	0.	0.	0.	0.
100			0.	0.				

(A) - AUTO DELETE:

Selecting this command will automatically delete all extraneous nodes, that is, all domain nodes outside the problems' boundaries as well as all nodes within holes or inner contours of the problem area.

(V) - VALUE:

CLYDE solves the problem's governing PDE for the values of the problem's variable at each inner domain node. The range of these values is displayed below the working area box. The user may select any VALUE within this range and the locations of all points within the problem area with this VALUE are displayed on the screen, with straight line segments joining adjacent points. The resulting display is an iso-Value contour. As many different contour VALUES as desired may be displayed, one at a time, one after the other.

(G) - RANGE:

This is the lazy man's (or efficient man's, depending upon your viewpoint) aid to many VALUE commands. A full RANGE of contours of values of the problems' variable may be chosen for display. The CLYDE program asks the user for the minimum value, the maximum value (both input with decimal points), and the number of different contour values to be plotted (in I3 format) including both the minimum and maximum values. Each of these three queries from CLYDE is answered, sequentially, followed by a R. For example,

100. R
300. R
005 R

will produce five contour maps for the values of 100, 150, 200, 250, and 300.

(X) -CROSS SECTION:

The CLYDE solution to a two-dimensional problem is a three dimensional surface. With this command a plane is "passed through" the two dimensional picture of the problem (and the surface) displayed on the screen. This plane is perpendicular to the screen and is shown as a straight line. CLYDE will generate a new display showing a CROSS-SECTION (or elevation) view of the surface from the edge or side. In this manner the variation or plot of the solution along that line is displayed on the screen. The location of the two points defining the line representing the cutting plane are input to the program by positioning the cross-hairs and depressing the space-bar. The program prompts or cues the user by displayed instructions. Upon completion of this command, the values of the slopes of the surface at the places where the cutting plane cuts the boundaries are calculated and displayed below the graphics command box.

(Z) - CROSS SECTION-MIRROR:

This command will produce CROSS SECTIONS automatically at all MIRROR lines without the need to position the cross-hairs.

(K) - COMB PLOT:

Similar to PLOT, but permits the COMBining of two or more PLOT files of the current working area display for use by a CalComp plotter.

(T) - RESTART (NODES):

The screen is cleared, the picture of the problem is redrawn with NODES shown, and the user may RESTART calling for displays of output plots of selected VALUES or RANGE of values, or of CROSS SECTIONS, or combinations of these.

(L) - RESTART (NO NODES):

Same as above, but picture is redrawn with NO NODES displayed.

(U) - MIRROR/UNMIRR:

Mirror, mirror, on the wall;
Which is the view preferred by all?
Obviously, not the one you see;
So change it with the big U key.

A symmetrical problem area or one with "repeating sections" may be input with mirror lines (ML) as line segments. After the problem matrix has been solved, either the repeating section or the full problem area (flipped or mirrored about the ML's) may be displayed. Whichever picture is being displayed, keying this command will produce the other one.

BOB & CLYDE VERSUS DOUBLE-KEYED SHAFT

AD-A046 155 ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND DOVER--ETC F/G 9/2
THE BOOK OF CLYDE WITH A TORQUE-ING CHAPTER.(U)
OCT 77 R I ISAKOWER, R E BARNAS
UNCLASSIFIED MISD-UM-77-3 NL

2 OF 2
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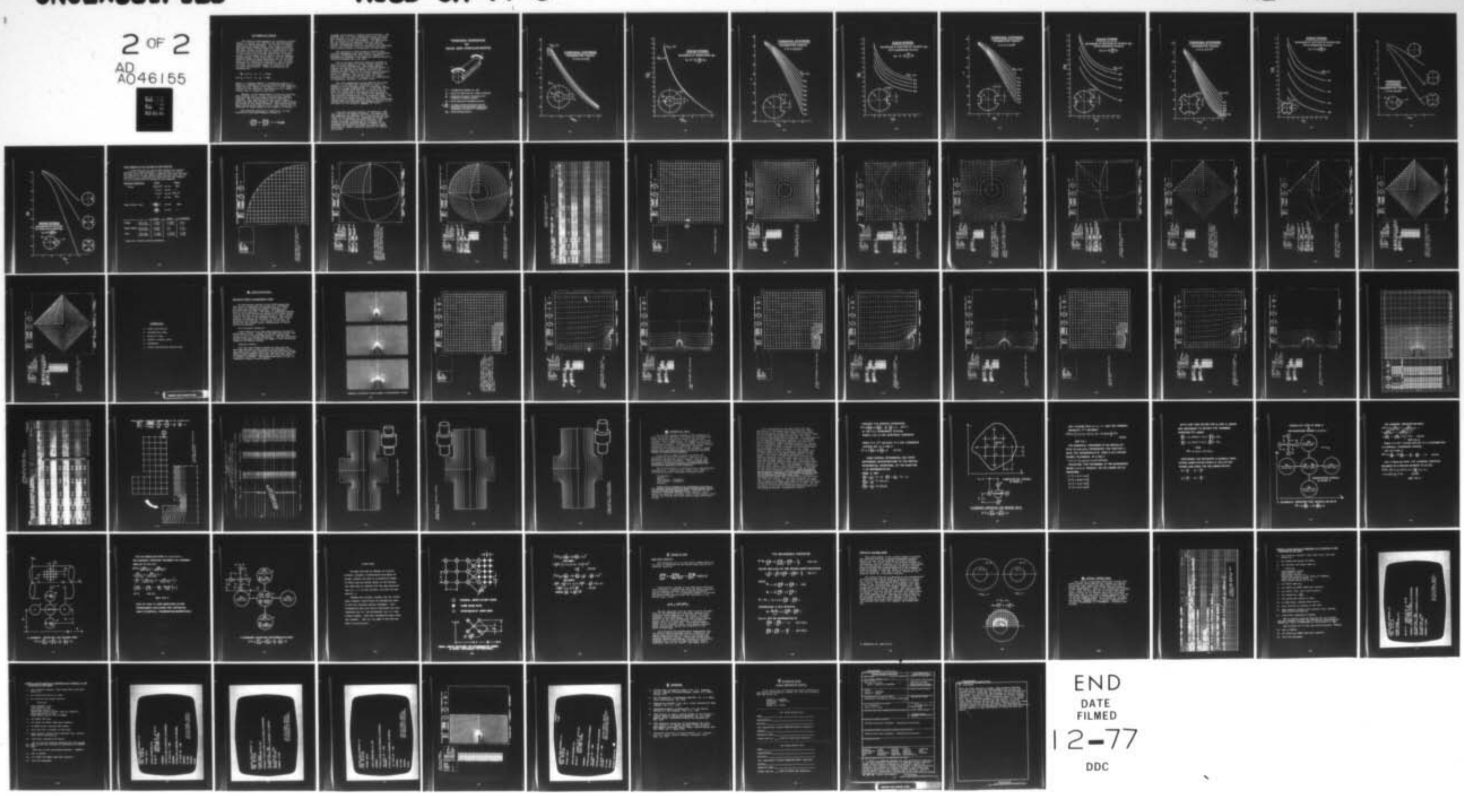
A046155



END
DATE
FILMED
12-77
DDC

THE TORQUE-ING CHAPTER

The elastic stress analysis of uniformly circular shafts in torsion is a familiar and straightforward concept to design engineers. As the bar is twisted, plane sections remain plane, radii remain straight, and each section rotates about the longitudinal axis. The shear stress at any point is proportional to the distance from the center and the stress vector lies in the plane of the circular section and is perpendicular to the radius to the point, with the maximum stress tangent to the outer face of the bar (another shearing stress of equal magnitude acts at the same point in the longitudinal direction). The torsional stiffness is a function of material property, angle of twist, and the polar moment of inertia of the circular cross-section. These relationships are expressed as:

$$\theta = T/J \cdot G, \quad \text{or} \quad T = G \cdot \theta \cdot J$$

$$\text{and } S_s = T \cdot r/J, \quad \text{or} \quad S_s = G \cdot \theta \cdot r$$

where T = twisting moment or transmitted torque; G = Modulus of Rigidity of the shaft material; θ = angle of twist per unit length of the shaft; J = polar moment of inertia of the (circular) cross-section; S_s = shear stress; and r = radius to any point.

However, if the cross-section of the bar deviates even slightly from a circle, the situation changes radically and far more complex design equations are required. Now, sections of the bar do not remain plane, but warp into surfaces, and radial lines through the center do not remain straight. The distribution of shear stress on the section is no longer linear and the direction of shear stress is not normal to a radius.

The governing equation of continuity (or compatibility) from Saint-Venant's theory is

$$\frac{\partial^2 \phi}{\partial X^2} + \frac{\partial^2 \phi}{\partial Y^2} = -2G\theta$$

where ϕ = Saint-Venant's torsion stress function. The problem then is to find a ϕ function which satisfies this equation and also the boundary conditions that ϕ = a constant along the boundary. This ϕ function has the nature of a potential function, such as voltage, hydrodynamic velocity, or gravitational height. Its absolute value is, therefore, not important; only relative values or differences are meaningful.

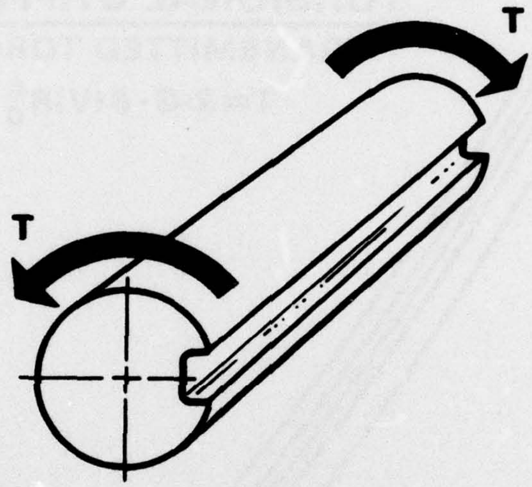
The solutions to this equation required complicated mathematics and even simple, but commonplace, practical cross-sections could not be reduced to mathematical formulae - and numerical approximations or intuitive methods had to be used.

One of the most effective numerical methods to solve for Saint-Venant's torsion stress function is that of finite differences. The CLYDE computer program was applied to a number of keywayed shafts to produce the dimensionless design charts on the following pages. Most of the charts required approximately 45 computer runs for plot data generation - but once completed, the design charts for that cross-section are good for virtually all combinations of dimensions, material, and shaft twist.

The three dimensional plot of ϕ over the cross-section is a surface and, with ϕ set to zero (a perfectly valid constant) along the periphery, the surface is a domb or ϕ membrane.* It has been proven that the transmitted torque (T) is proportional to twice the volume under the membrane and the stress (S_s) is proportional to the slope of the membrane in the direction perpendicular to the measured slope. For bars with solid cross-sections, the maximum stress (neglecting the stress concentration of sharp re-entrant corners which are relieved with generous fillets) is at the point on the periphery <u>nearest</u> the center.

*The best intuitive method, incidentally, came from Prandtl: the membrane analogy. He showed that the compatibility equation for a twisted bar was the "same" as the equation for a membrane stretched over a hole in a flat plate and then inflated. This concept provides a simple way to visualize the torsional stress characteristics of shafts of any cross-section relative to those of circular shafts for which an (exact) analytical solution is readily obtainable.

TORSIONAL PROPERTIES
OF
SOLID, NON-CIRCULAR SHAFTS



T = TRANSMITTED TORQUE (IN - LBS)

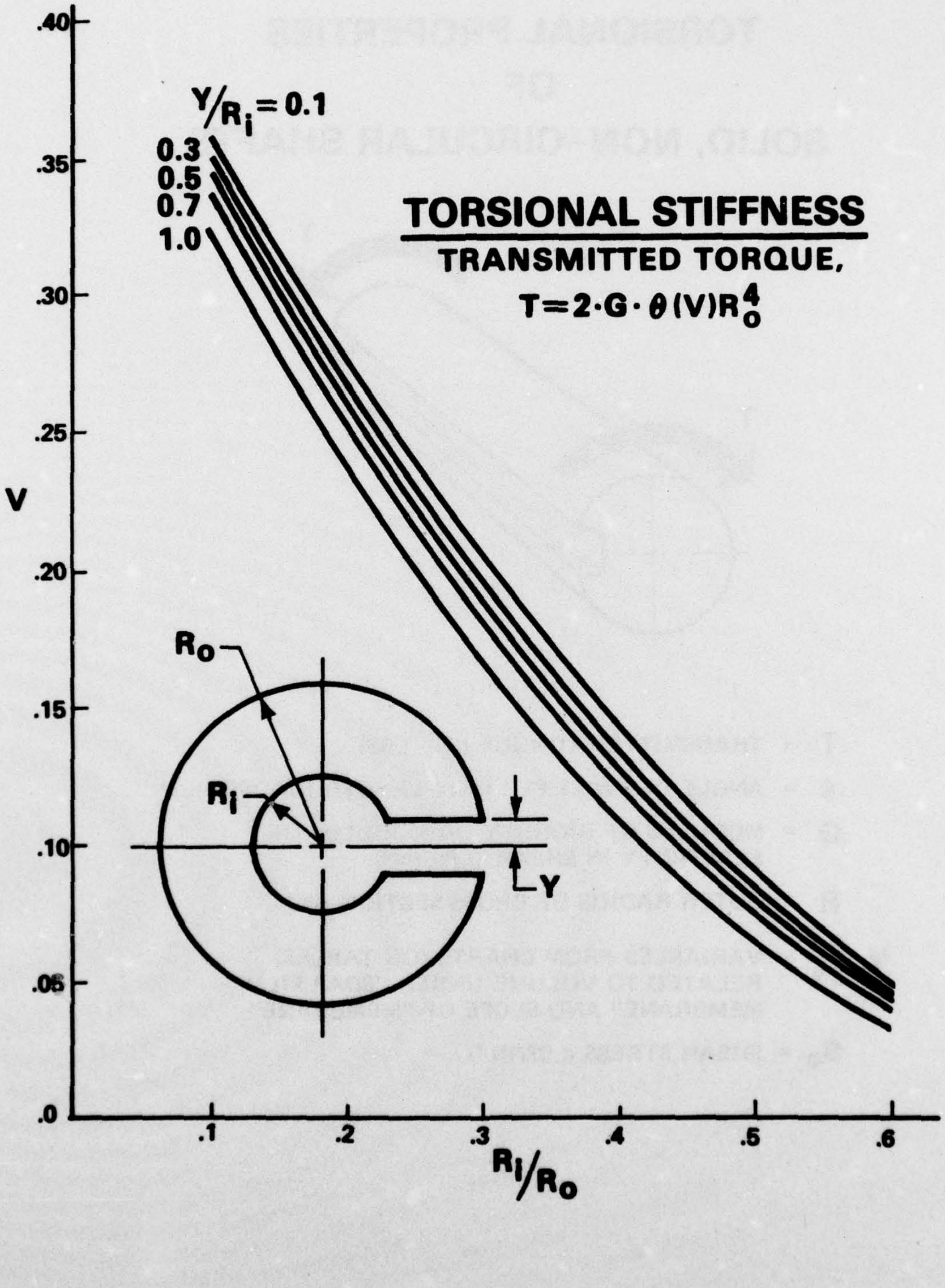
θ = ANGLE OF TWIST PER UNIT LENGTH (RADS/IN)

G = MODULUS OF RIGIDITY OR MODULUS OF ELASTICITY IN SHEAR (LBS/IN^2)

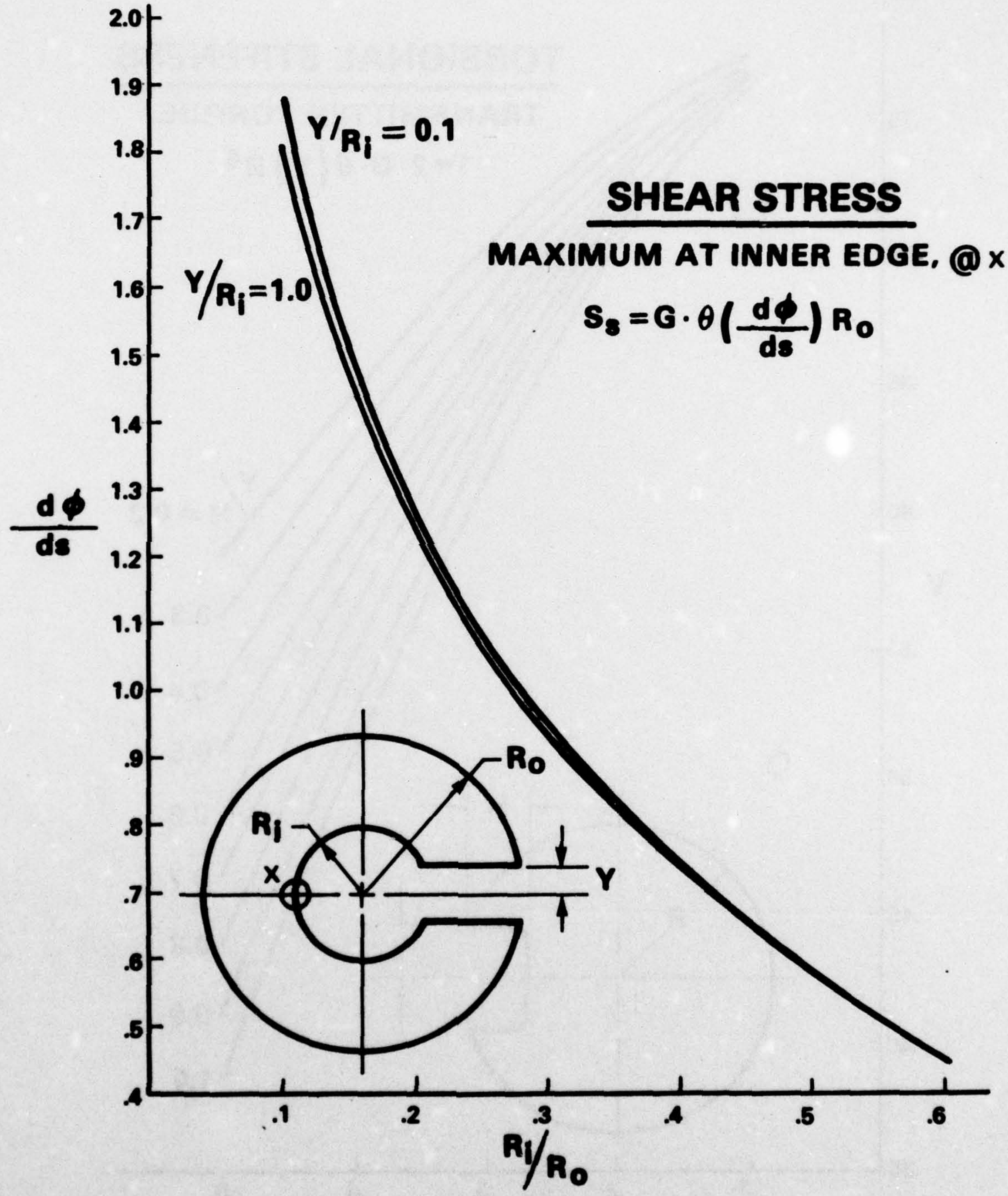
R = OUTER RADIUS OF CROSS-SECTION (IN)

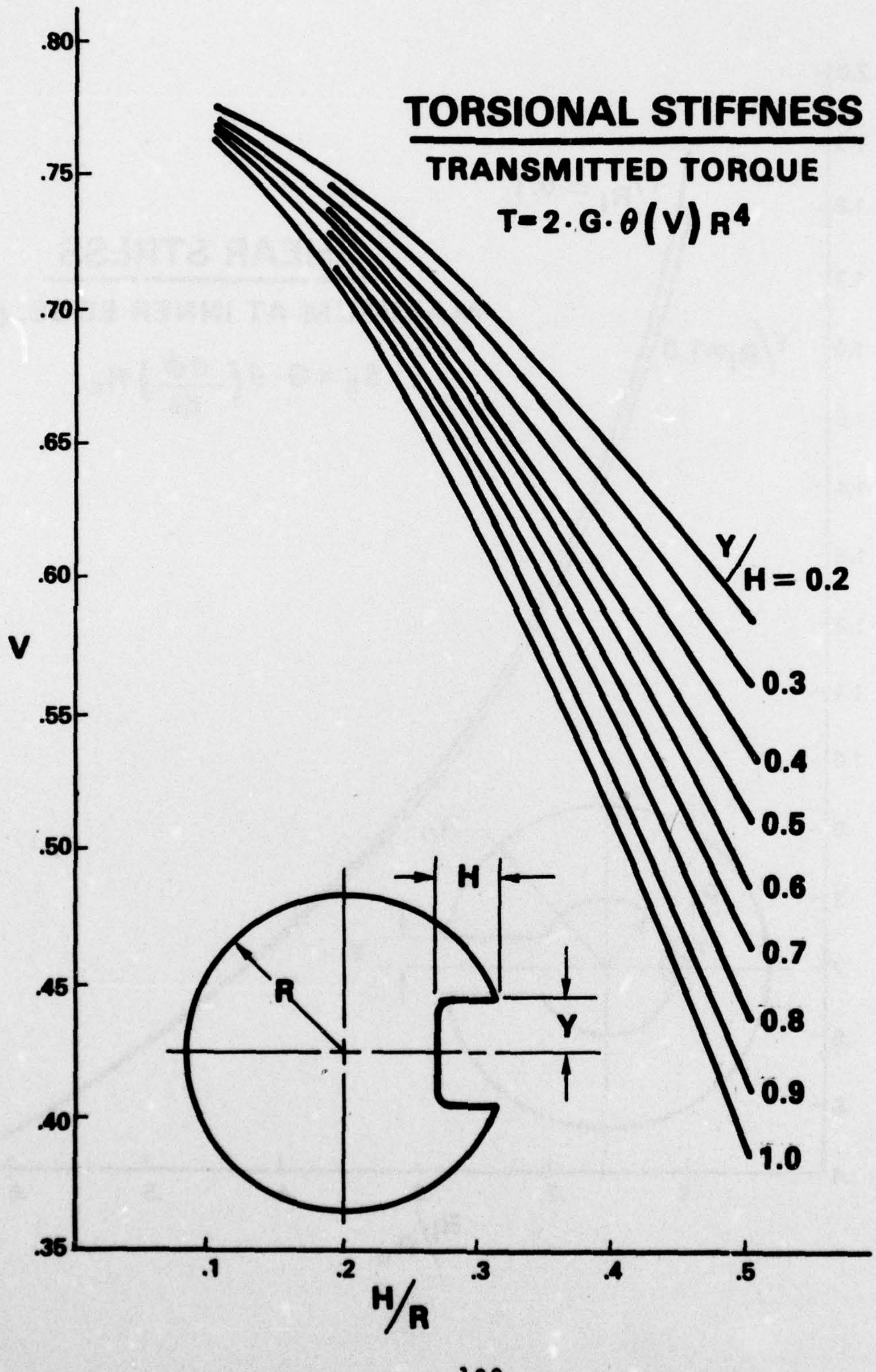
$V, \frac{d\phi}{ds}$ = VARIABLES FROM CHARTS (OR TABLES) RELATED TO VOLUME UNDER "SOAP FILM MEMBRANE" AND SLOPE OF "MEMBRANE"

S_s = SHEAR STRESS (LBS/IN^2)

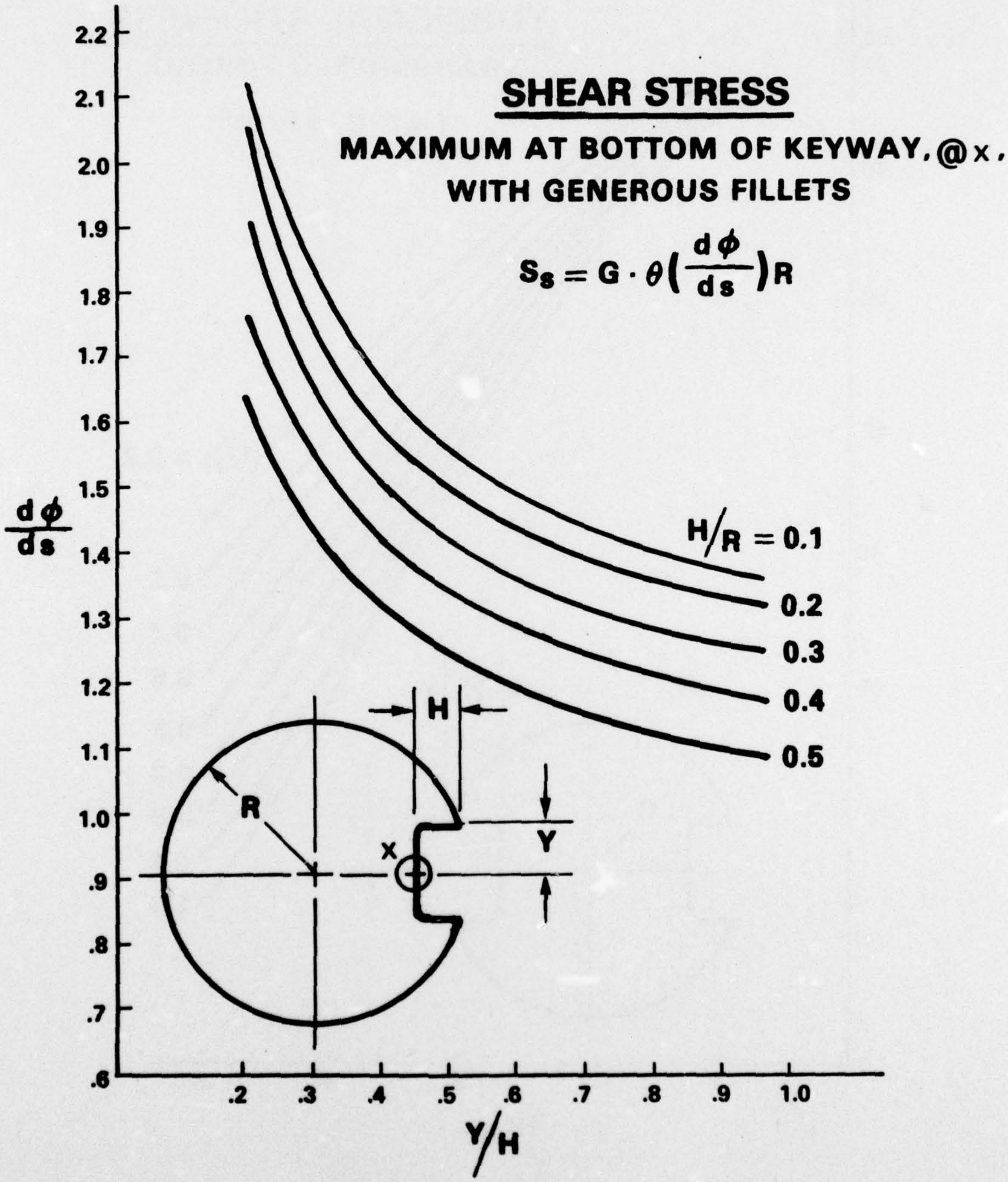


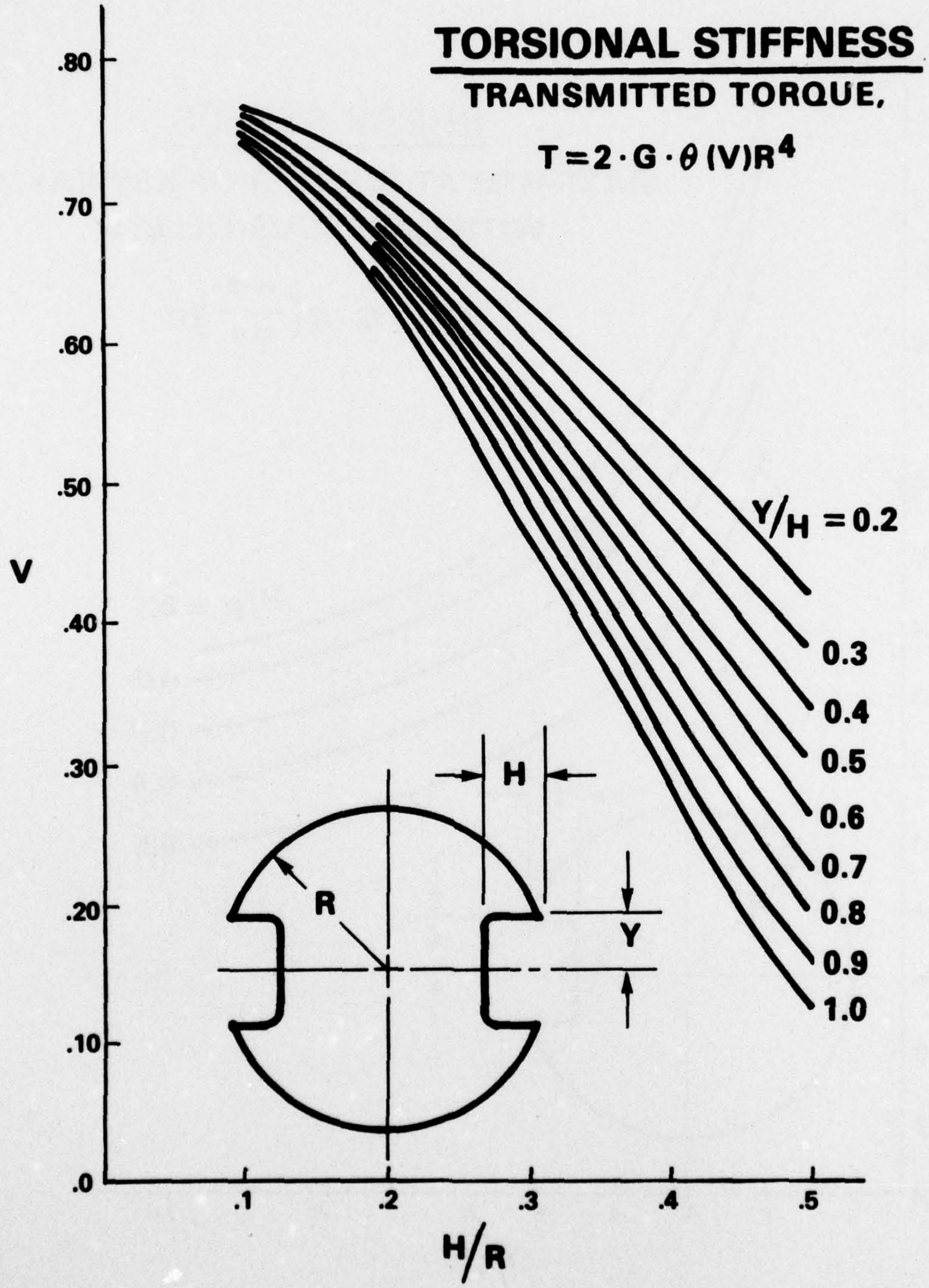
TORSIONAL STIFFNESS
TRANSMITTED TORQUE,
T=2·G·θ(V)R$_o^4$
Y/R$_i$ = 0.1
0.3
0.5
0.7
1.0
V
.40
.35
.30
.25
.20
.15
.10
.05
.0
.1
.2
.3
.4
.5
.6
R$_i$/R$_o$
R$_o$
R$_i$
Y

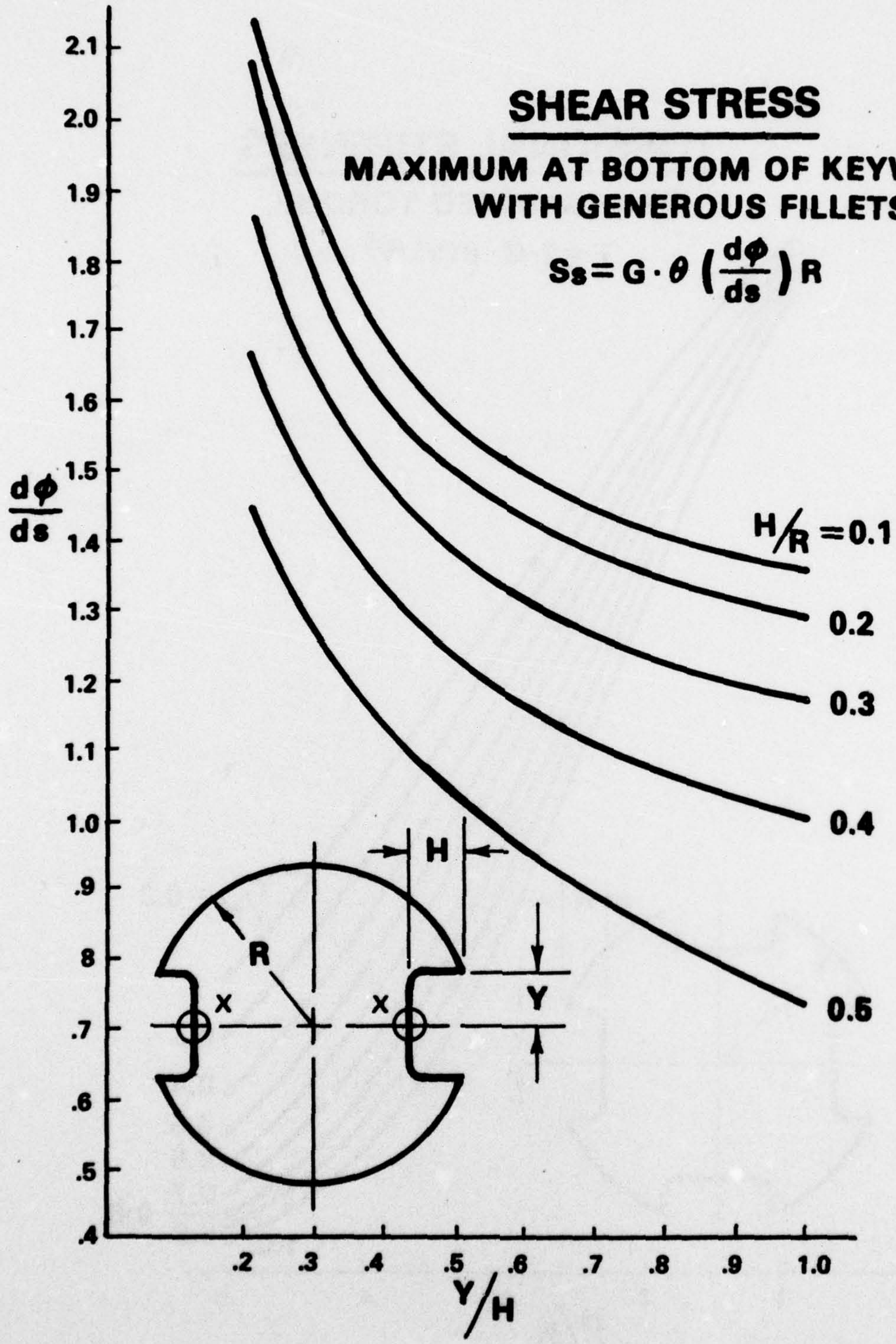

SHEAR STRESS
MAXIMUM AT INNER EDGE, @ X
$S_s = G \cdot \theta \left(\frac{d\phi}{ds}\right) R_o$
$Y/R_i = 0.1$
$Y/R_i = 1.0$
$\frac{d\phi}{ds}$
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.1
.2
.3
.4
.5
.6
R_i/R_o
R_o
R_i
X
Y

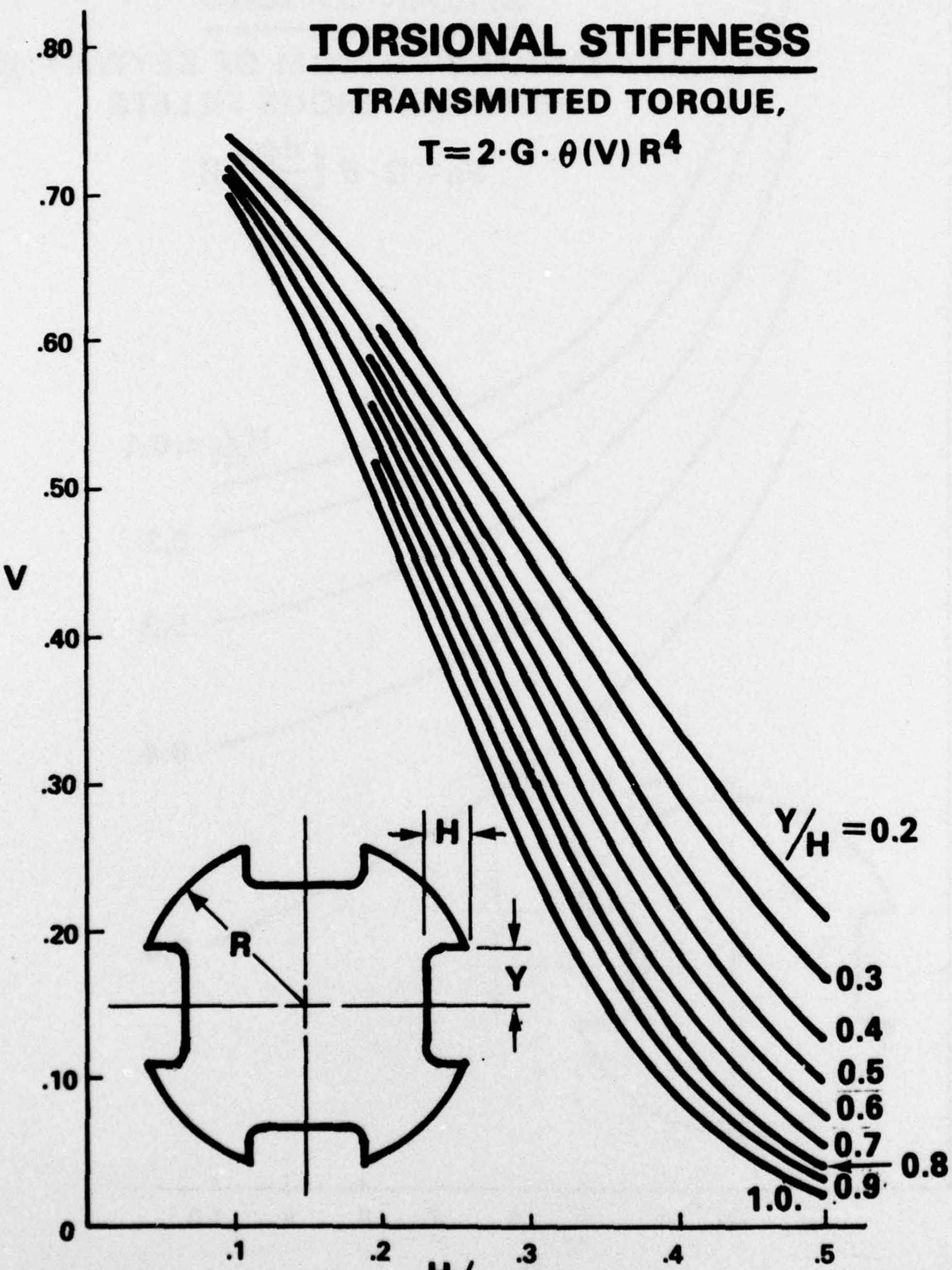


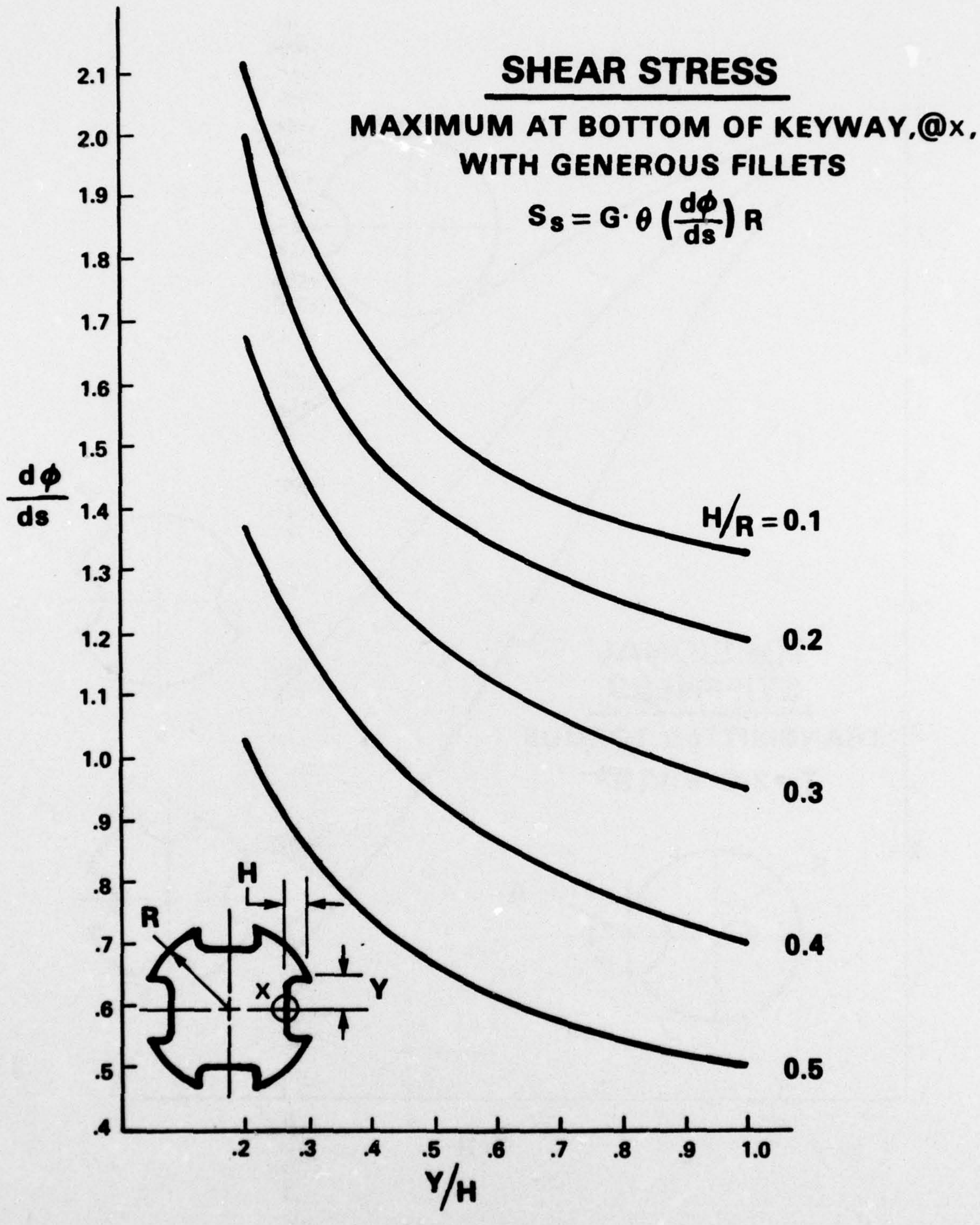
TORSIONAL STIFFNESS
TRANSMITTED TORQUE
T=2·G·θ(V) R4
Y/H = 0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
.80
.75
.70
.65
.60
.55
.50
.45
.40
.35
V
.1
.2
.3
.4
.5
H/R
H
R
Y

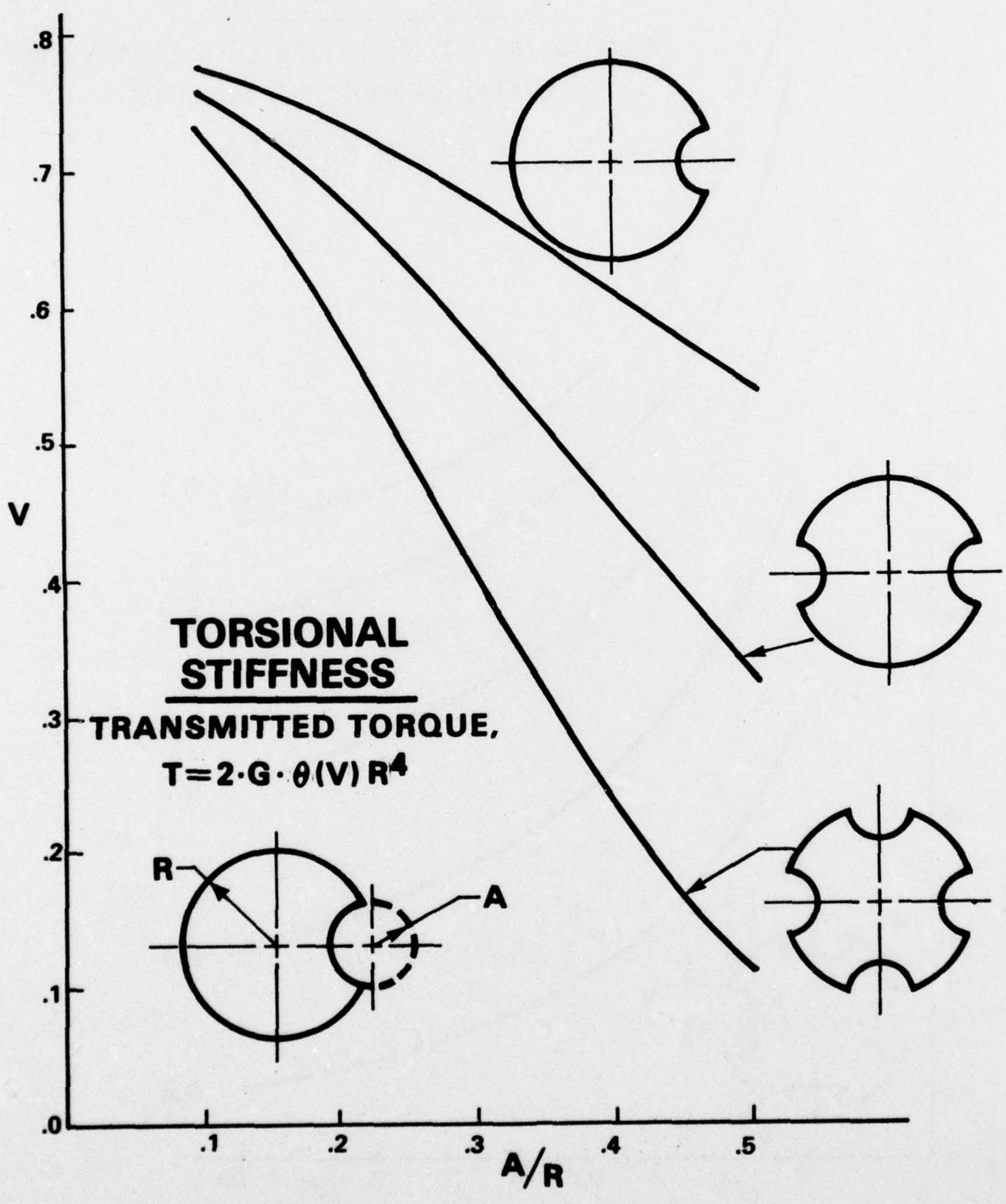

SHEAR STRESS
MAXIMUM AT BOTTOM OF KEYWAY, @ x,
WITH GENEROUS FILLETS
$S_s = G \cdot \theta \left(\frac{d\phi}{ds} \right) R$
$\frac{d\phi}{ds}$
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
H/R = 0.1
0.2
0.3
0.4
0.5
H
R
Y
X
.2
.3
.4
.5
.6
.7
.8
.9
1.0
Y/H


TORSIONAL STIFFNESS
TRANSMITTED TORQUE,
T=2·G·θ(V)R⁴
V
.80
.70
.60
.50
.40
.30
.20
.10
.0
.1
.2
.3
.4
.5
H/R
Y/H = 0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
H
R
Y

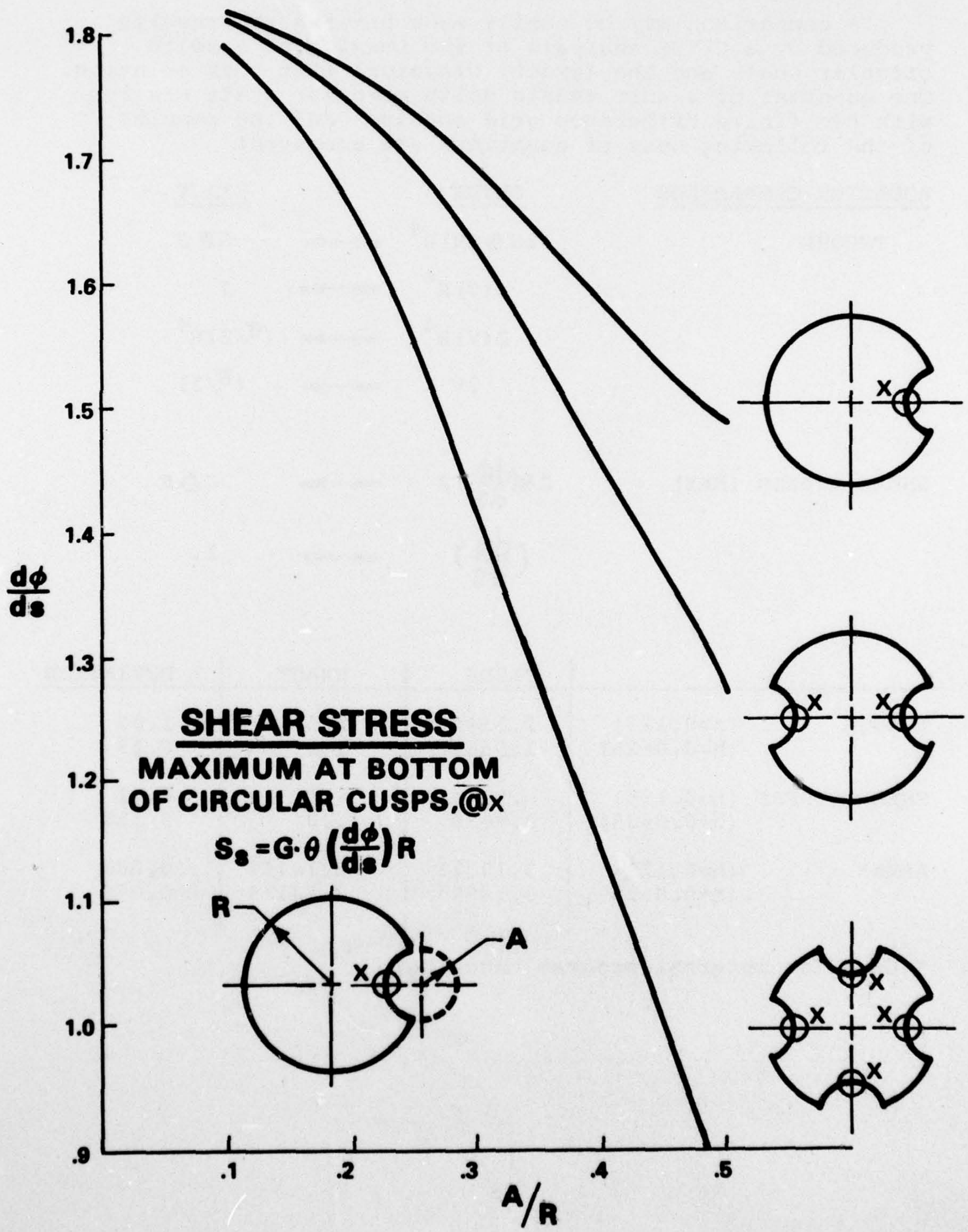

SHEAR STRESS
MAXIMUM AT BOTTOM OF KEYWAY, @ X,
WITH GENEROUS FILLETS
$S_s = G \cdot \theta \left(\frac{d\phi}{ds}\right) R$
$\frac{d\phi}{ds}$
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
8
.7
.6
.5
.4
.2
.3
.4
.5
.6
.7
.8
.9
1.0
Y/H
H/R = 0.1
0.2
0.3
0.4
0.5
H
R
X
X
Y


TORSIONAL STIFFNESS
TRANSMITTED TORQUE,
T=2·G·θ(V) R4
V
.80
.70
.60
.50
.40
.30
.20
.10
0
.1
.2
.3
.4
.5
H/R
Y/H =0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0.
H
R
Y


SHEAR STRESS
MAXIMUM AT BOTTOM OF KEYWAY,@x,
WITH GENEROUS FILLETS
$S_s = G \cdot \theta \left(\frac{d\phi}{ds}\right) R$
$\frac{d\phi}{ds}$
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
$H/R = 0.1$
0.2
0.3
0.4
0.5
H
R
X
Y
.2
.3
.4
.5
.6
.7
.8
.9
1.0
Y/H



.8
.7
.6
.5
V
.4
.3
.2
.1
.0
.1
.2
.3
.4
.5
A/R
TORSIONAL STIFFNESS
TRANSMITTED TORQUE,
T=2·G·θ(V) R4
R
A


SHEAR STRESS
MAXIMUM AT BOTTOM
OF CIRCULAR CUSPS, @x
$S_s = G \cdot \theta \left(\frac{d\phi}{ds}\right) R$
R
A
X
$\frac{d\phi}{ds}$
A/R
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.1
.2
.3
.4
.5

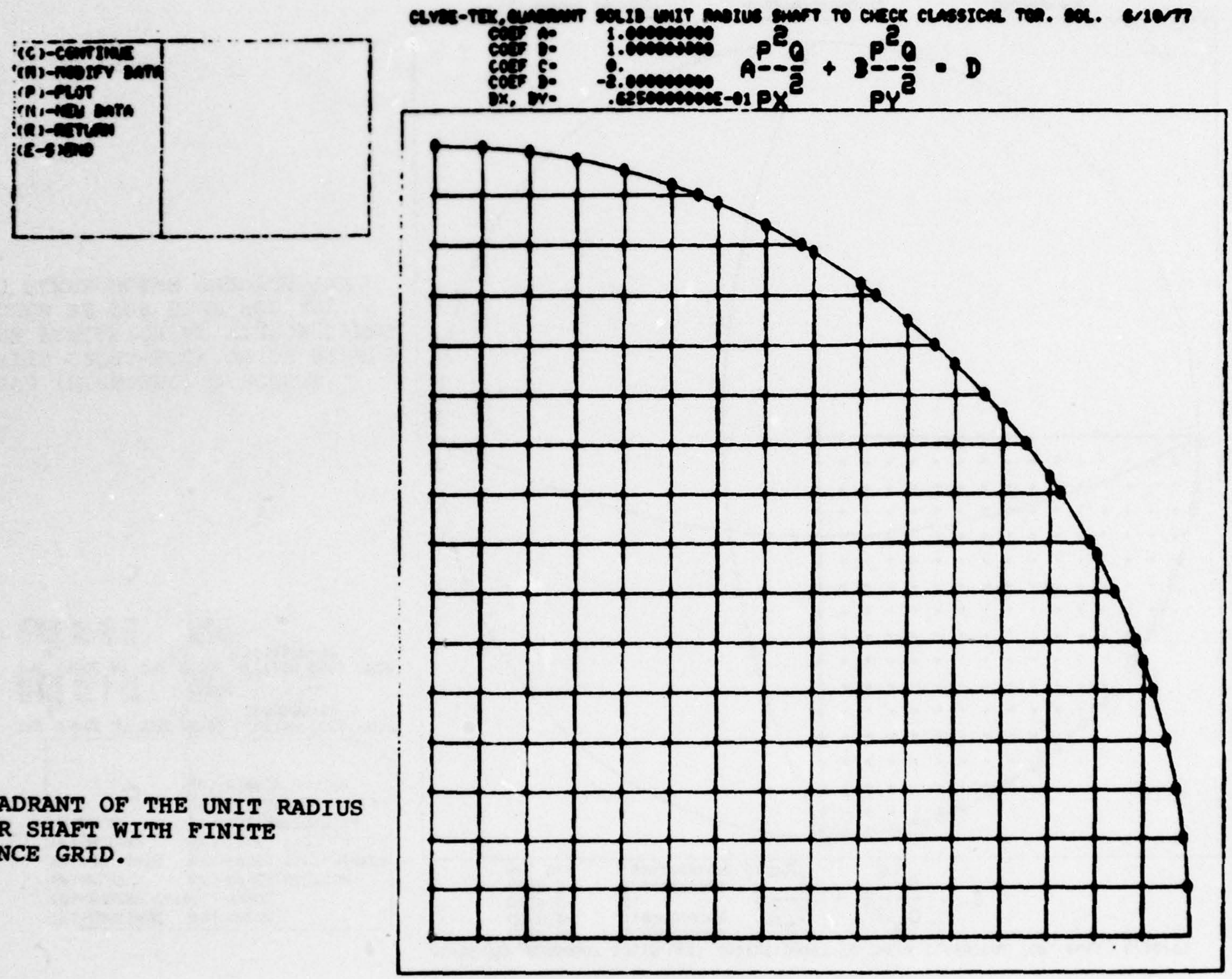
SOME COMMENTS ON THE ACCURACY OF THE SOLUTION

A comparison may be easily made between the results produced by a CLYDE analysis of the torsion of a solid circular shaft and the (exact) classical text book solution. One quadrant of a unit raduis solid circular shaft was run with two finite difference grid spacings and the results of the following sets of equations are compared:

EQUATION COMPARISON	CLYDE		EXACT
TORQUE	$2G\theta(V)R^4$	$\longleftrightarrow$	$G\theta J$
	$2(V)R^4$	$\longleftrightarrow$	J
	$2(V)R^4$	$\longleftrightarrow$	$(\pi/2)R^4$
	$2V$	$\longleftrightarrow$	$(\pi/2)$
SHEAR STRESS (MAX)	$G\theta(\frac{d\phi}{ds})R$	$\longleftrightarrow$	$G\theta R$
	$(\frac{d\phi}{ds})$	$\longleftrightarrow$	$1.$

		CLYDE	EXACT	% DEVIATION
TORQUE	(h=0.125)	1.5546	1.5708	1.03
	(h=0.0625)	1.5669	1.5708	0.25
SHEAR STRESS	(h=0.125)	0.9379	1.0	6.21
	(h=0.0625)	0.9688	1.0	3.125
AREA*	(h=0.125)	3.13316	3.14159	0.268
	(h=0.0625)	3.13984	3.14159	0.056

*(Used for internal program checking)



$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$

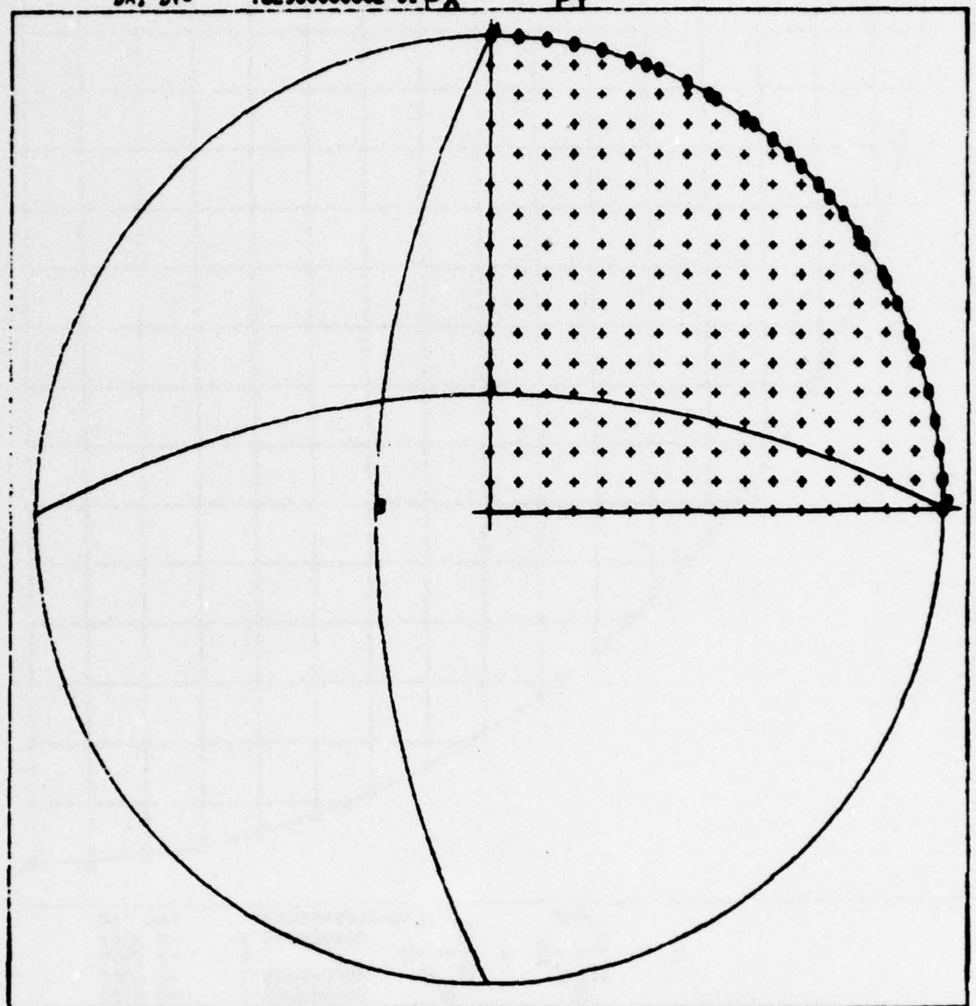
ONE QUADRANT OF THE UNIT RADIUS CIRCULAR SHAFT WITH FINITE DIFFERENCE GRID.

```
CLYDE-TEX,QUADRANT SOLID UNIT RADIUS SHAFT TO CHECK CLASSICAL TOR. SOL.  6/10/77
          COEF A=     1.000000000
          COEF B=     1.000000000
          COEF C=     6.
          COEF D=    -2.000000000
          DX, DY=     .6250000000E-01
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$

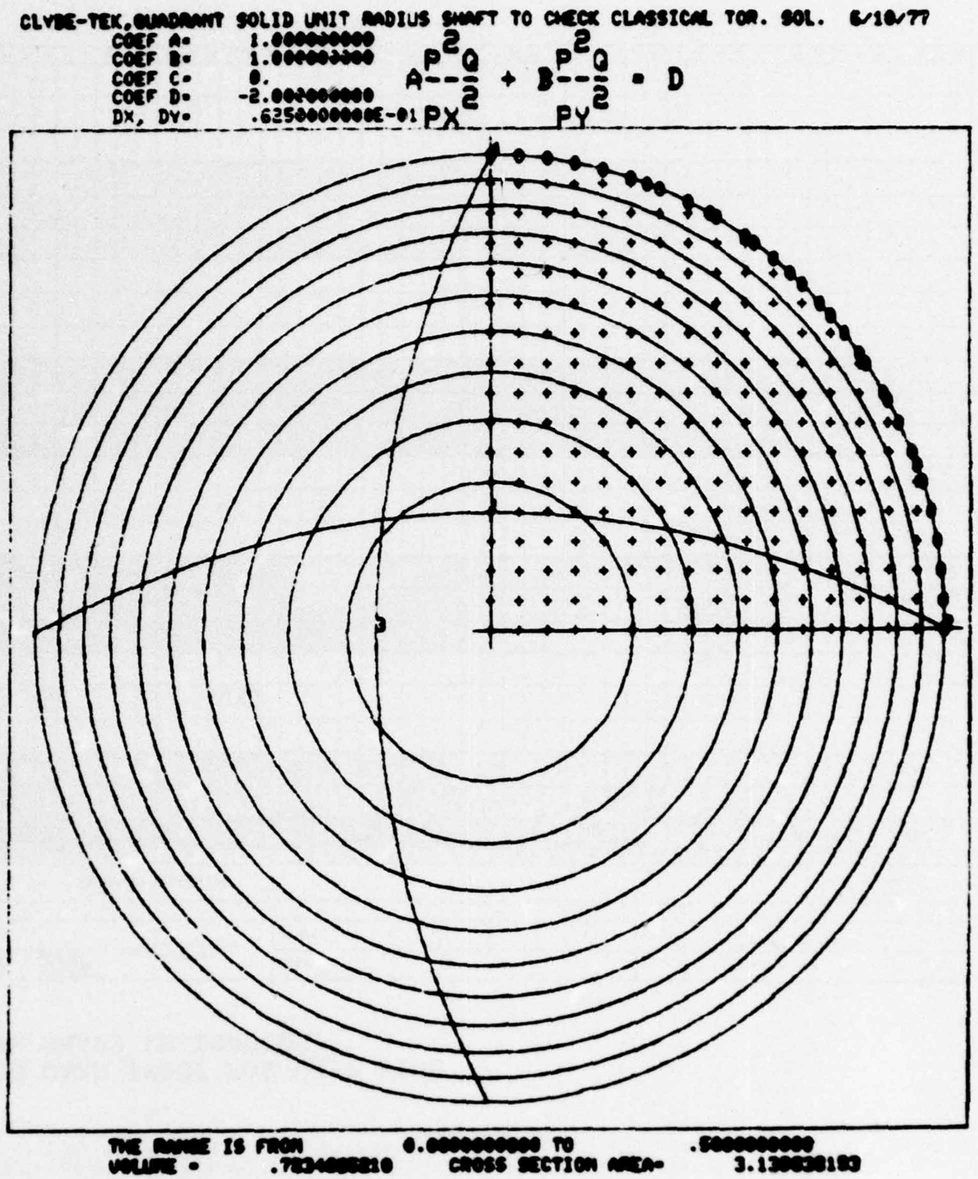
```
(C)-CONTINUE     (V)-VALUE
(M)-MODIFY DATA  (G)-RANGE
(P)-PLOT         (X)-CROSS SECTION
(N)-NEW DATA     (Z)-CROSS SECT-MIRROR
(R)-RETURN       (K)-COMB. PLOT
(E-S)END         (T)-RESTART(NODES)
                 (L)-RESTART(NO NODES)
                 (U)-MIRROR/UNMIRR

THE RANGE AT THE CROSS SECTION GOES FROM
  0.              TO        .500000E+00
SLOPE AT 1 IS     -.03124
SLOPE AT 2 IS      .96875
THE RANGE AT THE CROSS SECTION GOES FROM
  0.              TO        .500000E+00
SLOPE AT 3 IS     -.03125
SLOPE AT 4 IS      .96875
```



```
THE RANGE IS FROM        0.0000000000 TO        .5000000000
VOLUME =      .7834085210     CROSS SECTION AREA=     3.1380838193
```

COMPLETE (MIRRORED) CIRCULAR SHAFT WITH CROSS-SECTION OF STRESS FUNCTION VARIATION AT MIRROR LINES. THIS WOULD BE THE SAME FOR ANY CUTTING PLANE GOING THROUGH THE CENTER.




```
(C)-CONTINUE       (V)-VALUE
(M)-MODIFY DATA    (G)-RANGE
(P)-PLOT           (X)-CROSS SECTION
(N)-NEW DATA       (Z)-CROSS SECT-MIRROR
(R)-RETURN         (K)-COMB. PLOT
(E-S)END           (T)-RESTART(NODES)
                   (L)-RESTART(NO NODES)
                   (U)-MIRROR/UNMIRR
THE RANGE AT THE CROSS SECTION GOES FROM
    0.             TO      .500000E+00
SLOPE AT 1 IS     -.03124
SLOPE AT 2 IS      .96875
THE RANGE AT THE CROSS SECTION GOES FROM
    0.             TO      .500000E+00
SLOPE AT 3 IS     -.03125
SLOPE AT 4 IS      .96875
ENTER MINIMUM :  .05
ENTER MAXIMUM :  .45
ENTER NO. OF CONTOURS: 009
009
                   .500000E-01
                   .100000E+00
                   .150000E+00
                   .200000E+00
                   .250000E+00
                   .300000E+00
                   .350000E+00
                   .400000E+00
                   .450000E+00
```

CONTOUR MAPS OF CONSTANT STRESS FUNCTION VALUES ADDED.

PUNCH CARD INPUT FOR UNIT SIDE
SQUARE SHAFT IN TORSION.

PROGRAM: CLYDE-TEK INPUT, TØRSIØN ØF
PROGRAMMER: SQUARE SHAFT

PUNCHING INSTRUCTIONS	GRAPHIC		PAGE OF
	PUNCH		CARD ELECTRO NUMBER

DATE

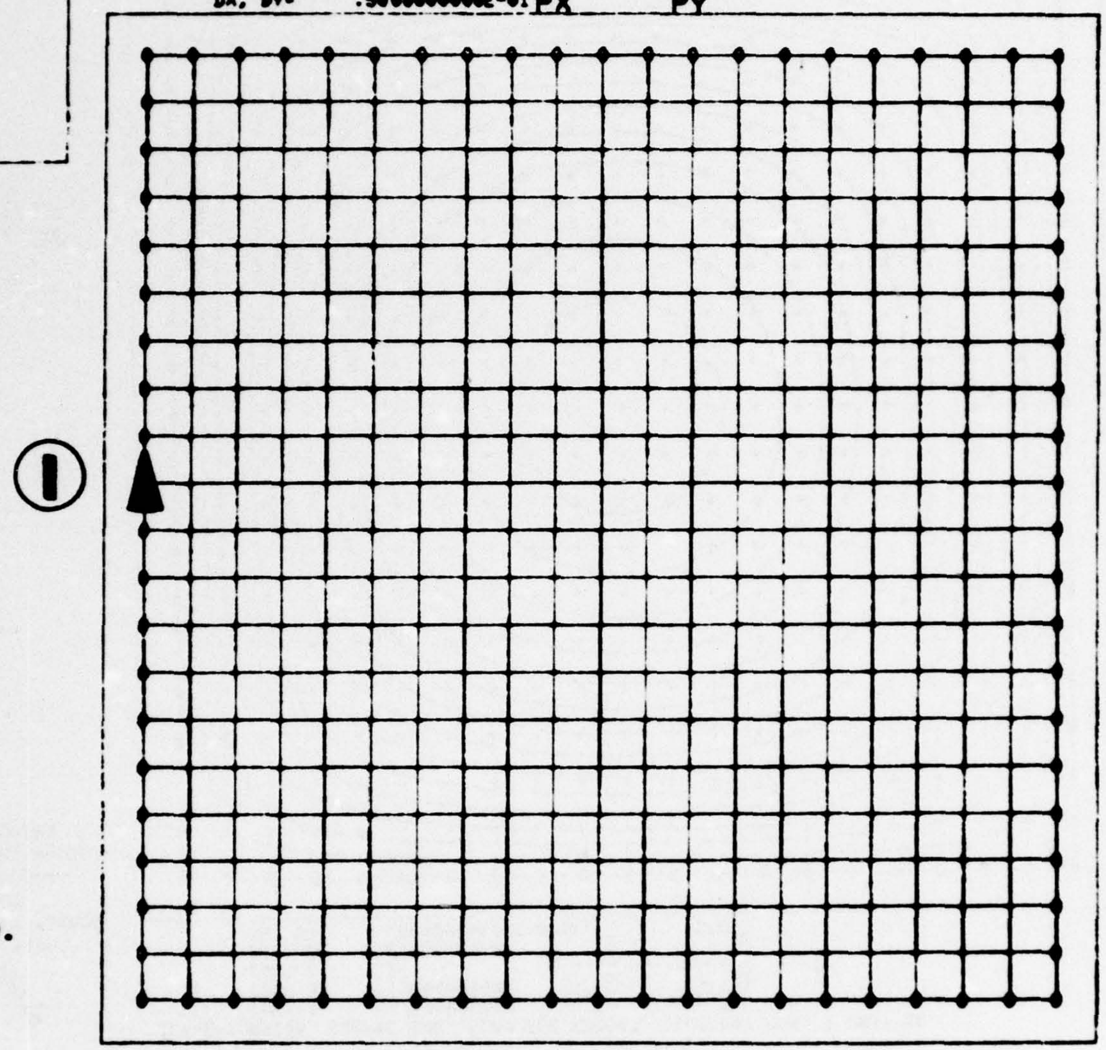
STATEMENT NUMBER	FORTRAN STATEMENT	IDENTIFICATION SEQUENCE
[illegible]	[illegible] ILLUSTRATIONS. 1 UNIT SQ., DX	=.05
[illegible]	[illegible] 0.05 [illegible] 1.0 0.0 -2.0	
1 [illegible]	[illegible] 1.0	
	0.0 0.0	
2 SL	0.0 1.0 1.0 1.0	
	0.0 0.0	
[illegible]	[illegible]	
[illegible]	[illegible]	
[illegible]	[illegible]	
	0.0 0.0	

(C)-CONTINUE
(M)-MODIFY DATA
(P)-PLOT
(N)-NEW DATA
(R)-RETURN
(E-S)END

CLYDE-TORSION, SQUARE BAR, DEMO FOR REPORT ILLUSTRATIONS. 1 UNIT SQ., DX = .05

COEF A= 1.000000000
COEF B= 1.000000000
COEF C= 0.
COEF D= -2.000000000
DX, DY= .5000000000E-01

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



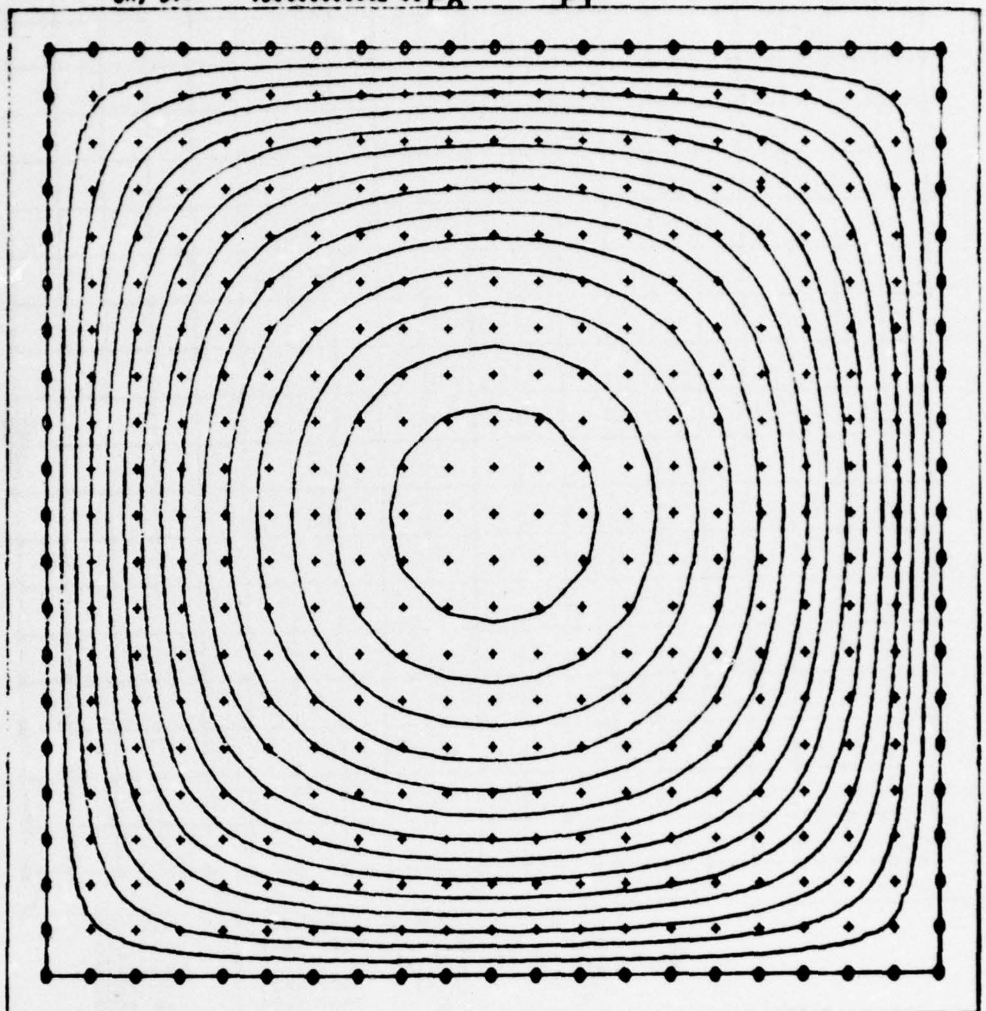
FINITE DIFFERENCE GRID.

```
(C)-CONTINUE         (V)-VALUE
(M)-MODIFY DATA      (G)-RANGE
(P)-PLOT             (X)-CROSS SECTION
(N)-NEW DATA         (Z)-CROSS SECT-MIRROR
(P)-RETURN           (K)-COMB. PLOT
(E-S)END             (T)-RESTART(NODES)
                     (L)-RESTART(NO NODES)
                     (U)-MIRROR/UNMIRR

ENTER MINIMUM = .01
ENTER MAXIMUM = .14
ENTER NO. OF CONTOURS= 014
014
                     .1[illegible]E-01
                     .2[illegible]E-01
                     .3[illegible]E-01
                     .4[illegible]E-01
                     .5[illegible]E-01
                     .6[illegible]E-01
                     .7[illegible]E-01
                     .8[illegible]E-01
                     .9[illegible]E-01
                     .10[illegible]E+00
                     .11[illegible]E+00
                     .12[illegible]E+00
                     .13[illegible]E+00
                     .14[illegible]E+00
```

```
CLYDE-TORSION, SQUARE BAR, DEMO FOR REPORT ILLUSTRATIONS. 1 UNIT SQ.,
     COEF A=     1.000000000
     COEF B=     1.000000000
     COEF C=     0.
     COEF D=    -2.000000000
     DX, DY=     .5000000000E-01
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



```
THE RANGE IS FROM        0.0000000000 TO          .1470534185
VOLUME =      .8871418854E-01 CROSS SECTION AREA=      .8800000000
```

FULL RANGE, USING (G) KEY, OF
CONSTANT STRESS FUNCTION LINES.

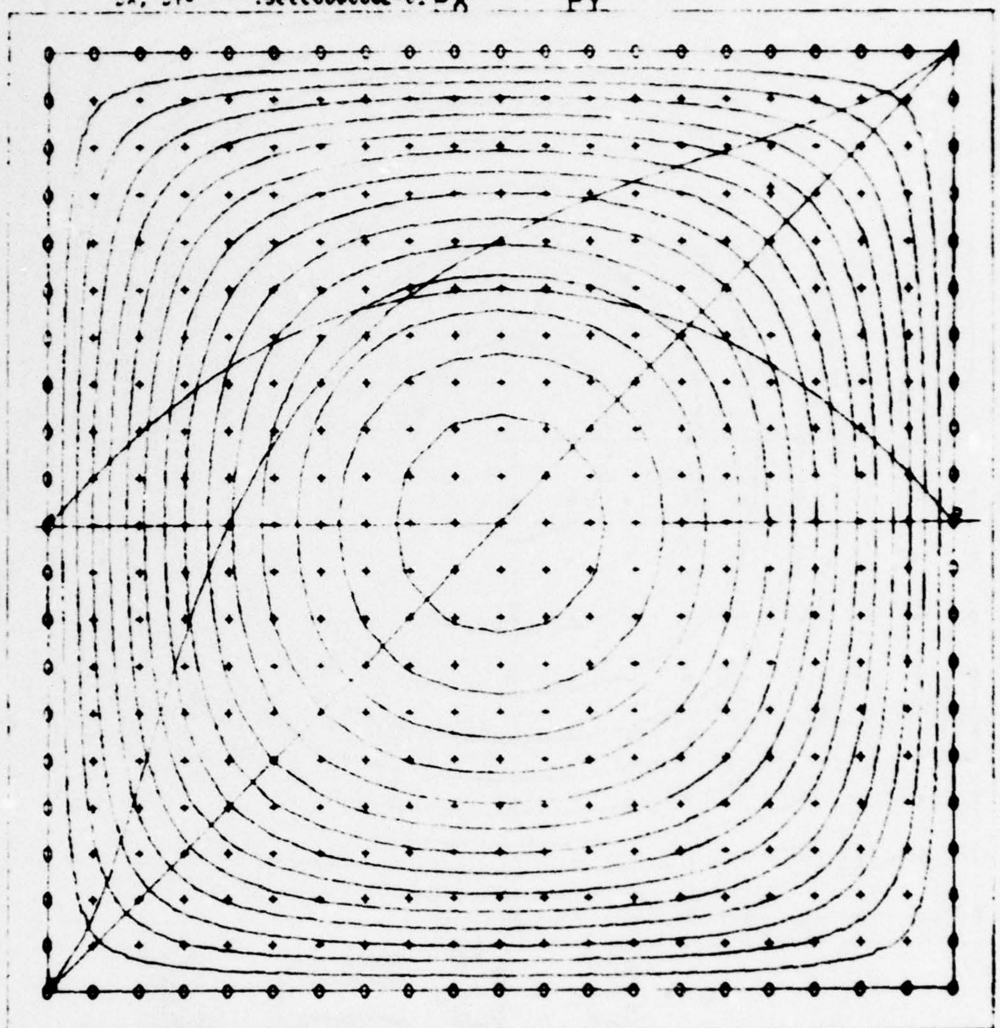
```
(C)-CONTINUE     (V)-VALUE
(M)-MODIFY DATA  (G)-RANGE
(P)-PLOT         (X)-CROSS SECTION
(N)-NEW DATA     (Z)-CROSS SECT-MIRROR
(R)-RETURN       (K)-COMB. PLOT
 E-S)END         (T)-RESTART(NODES)
                 (L)-RESTART(NO NODES)
                 (U)-MIRROR/UNMIRR

ENTER MINIMUM = .01
ENTER MAXIMUM = .14
ENTER NO. OF CONTOURS= 014
014
                 .10000000E-01
                 .20000000E-01
                 .30000000E-01
                 .40000000E-01
                 .50000000E-01
                 .60000000E-01
                 .70000000E-01
                 .80000000E-01
                 .90000000E-01
                 .10000000E+00
                 .11000000E+00
                 .12000000E+00
                 .13000000E+00
                 .14000000E+00
MOVE CROSS HAIR TO 1ST PT. OF CUTTING LINE
MOVE CROSS HAIR TO 2ND PT. OF CUTTING LINE
THE RANGE AT THE CROSS SECTION GOES FROM
   0.            TO        .147053E+00
SLOPE AT 1 IS      .62564
SLOPE AT 2 IS      .62560
MOVE CROSS HAIR TO 1ST PT. OF CUTTING LINE
MOVE CROSS HAIR TO 2ND PT. OF CUTTING LINE
THE RANGE AT THE CROSS SECTION GOES FROM
   0.            TO        .147053E+00
SLOPE AT 3 IS      .06069
SLOPE AT 4 IS      .07490
```

CROSS-SECTION VIEWS ADDED, USING (X) KEY.

```
CLYDE-TORSION, SQUARE BAR, DEMO FOR REPORT ILLUSTRATIONS. 1 UNIT SQ.,
        COEF A=     1.000000000
        COEF B=     1.000000000
        COEF C=     0.
        COEF D=    -2.000000000
        DX, DY=     .5000000000E-01
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



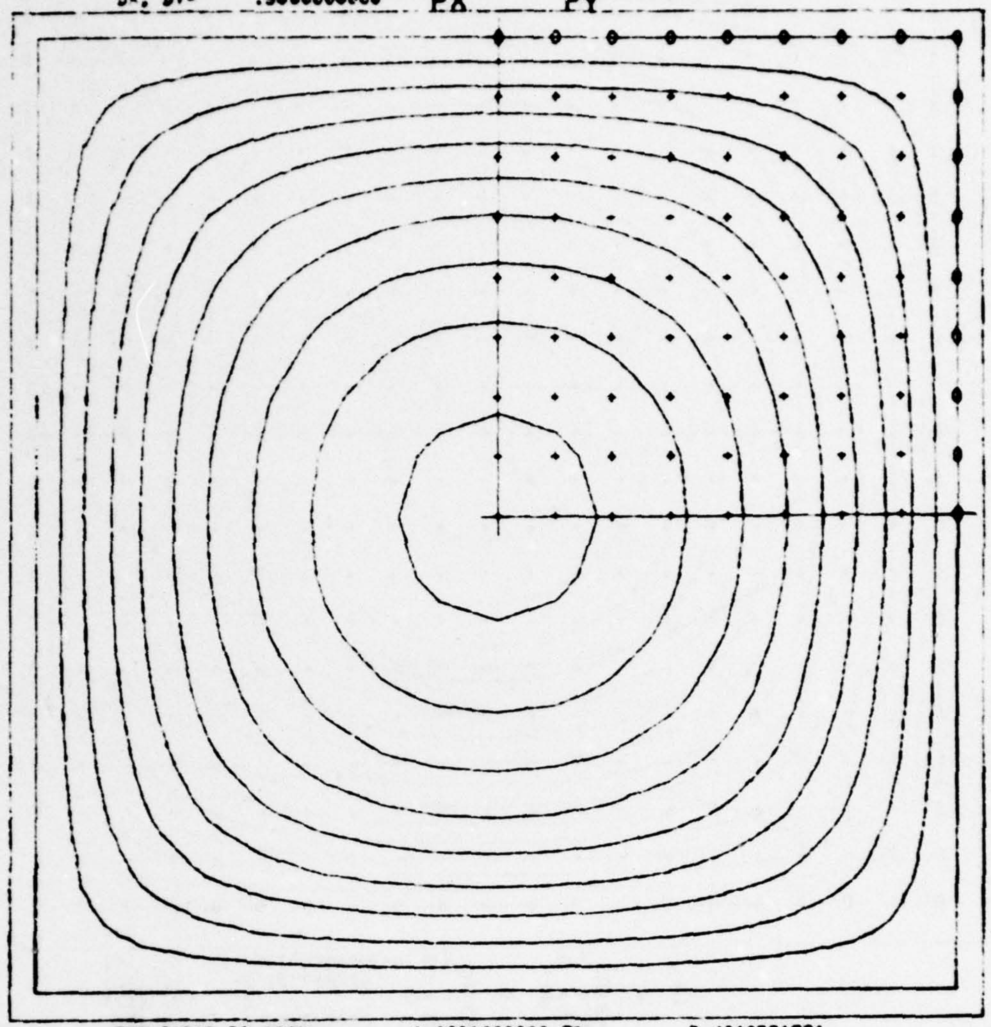
```
THE RANGE IS FROM        0.0000000000 TO        .1470534185
VOLUME =       .6971418254E-01 CROSS SECTION AREA=     .9960000000
```

```
CLYDE-TEK, TORSION OF SOLID SQUARE SHAFT 8 IN. (0 DEG)
     COEF A=     1.000000000
     COEF B=     1.000000000
     COEF C=     0.
     COEF D=    -2.000000000
     DX, DY=     .5000000000
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$

```
(C)-CONTINUE     (V)-VALUE
(M)-MODIFY DATA  (G)-RANGE
(P)-PLOT         (X)-CROSS SECTION
(N)-NEW DATA     (Z)-CROSS SECT-MIRROR
(R)-RETURN       (K)-COMB. PLOT
(E-S)END         (T)-RESTART(NODES)
                 (L)-RESTART(NO NODES)
                 (U)-MIRROR/UNMIRR

ENTER MINIMUM = 1.
ENTER MAXIMUM = 9.
ENTER NO. OF CONTOURS= 009
009
                   .10000000E+01
                   .20000000E+01
                   .30000000E+01
                   .40000000E+01
                   .50000000E+01
                   .60000000E+01
                   .70000000E+01
                   .80000000E+01
                   .90000000E+01
```



```
THE RANGE IS FROM          0.0000000000 TO          9.4010681221
VOLUME =        284.2190260     CROSS SECTION AREA=      63.50000000
```

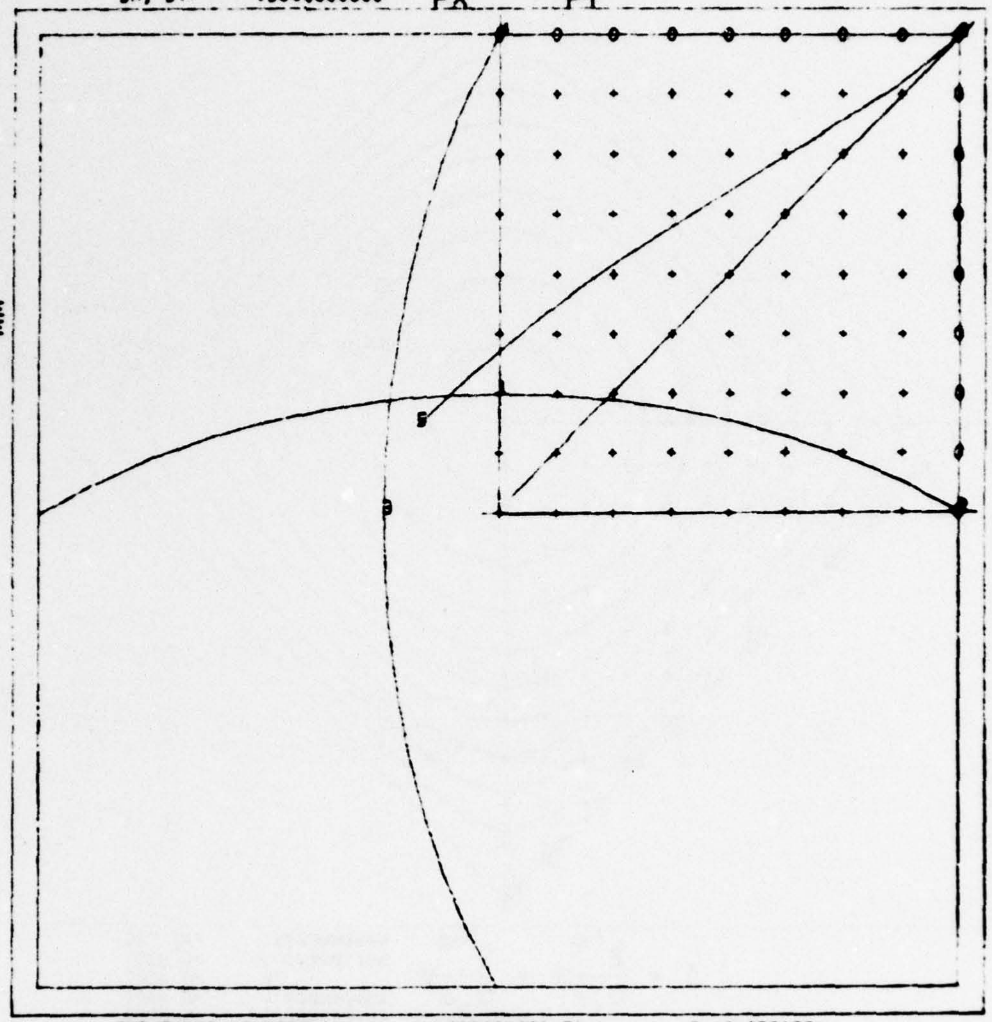
THIS IS AN "ORIENTATION" COMPARISON. FIRST, CONSIDER A SQUARE SHAFT, 8 INCHES ON A SIDE, POSITIONED AS SHOWN.

WITH A 0.5 INCH GRID, THE TORQUE RELATED VOLUME IS 284.22 CUBIC INCHES.

```
(C)-CONTINUE      (V)-VALUE
(M)-MODIFY DATA   (G)-RANGE
(P)-PLOT          (X)-CROSS SECTION
(N)-NEW DATA      (Z)-CROSS SECT-MIRROR
(R)-RETURN        (K)-COMB. PLOT
(E-S)END          (T)-RESTART(NODES)
                  (L)-RESTART(NO NODES)
                  (U)-MIRROR/UNMIRR
THE RANGE AT THE CROSS SECTION GOES FROM
   0.              TO      .940105E+01
SLOPE AT 1 IS    -.24995
SLOPE AT 2 IS    4.90619
THE RANGE AT THE CROSS SECTION GOES FROM
   0.              TO      .940108E+01
SLOPE AT 3 IS    -.25000
SLOPE AT 4 IS    4.90619
MOVE CROSS HAIR TO 1ST PT. OF CUTTING LINE
MOVE CROSS HAIR TO 2ND PT. OF CUTTING LINE
THE RANGE AT THE CROSS SECTION GOES FROM
   0.              TO      .939413E+01
SLOPE AT 5 IS    -.02898
SLOPE AT 6 IS     .63986
```

```
CLYDE-TEK, TORSION OF SOLID SQUARE SHAFT 8 IN. (0 DEG)
     COEF A=     1.000000000
     COEF B=     1.000000000
     COEF C=     0.
     COEF D=    -2.000000000
     DX, DY=      .5000000000
```

$$A\frac{P^2 Q}{PX^2} + B\frac{P^2 Q}{PY^2} = D$$



```
THE RANGE IS FROM          0.0000000000 TO          9.4010581221
VOLUME =       284.2190869     CROSS SECTION AREA=     63.50000000
```

CRITICAL STRESS SLOPES ARE 4.906
AT MIDDLE OF SIDES.

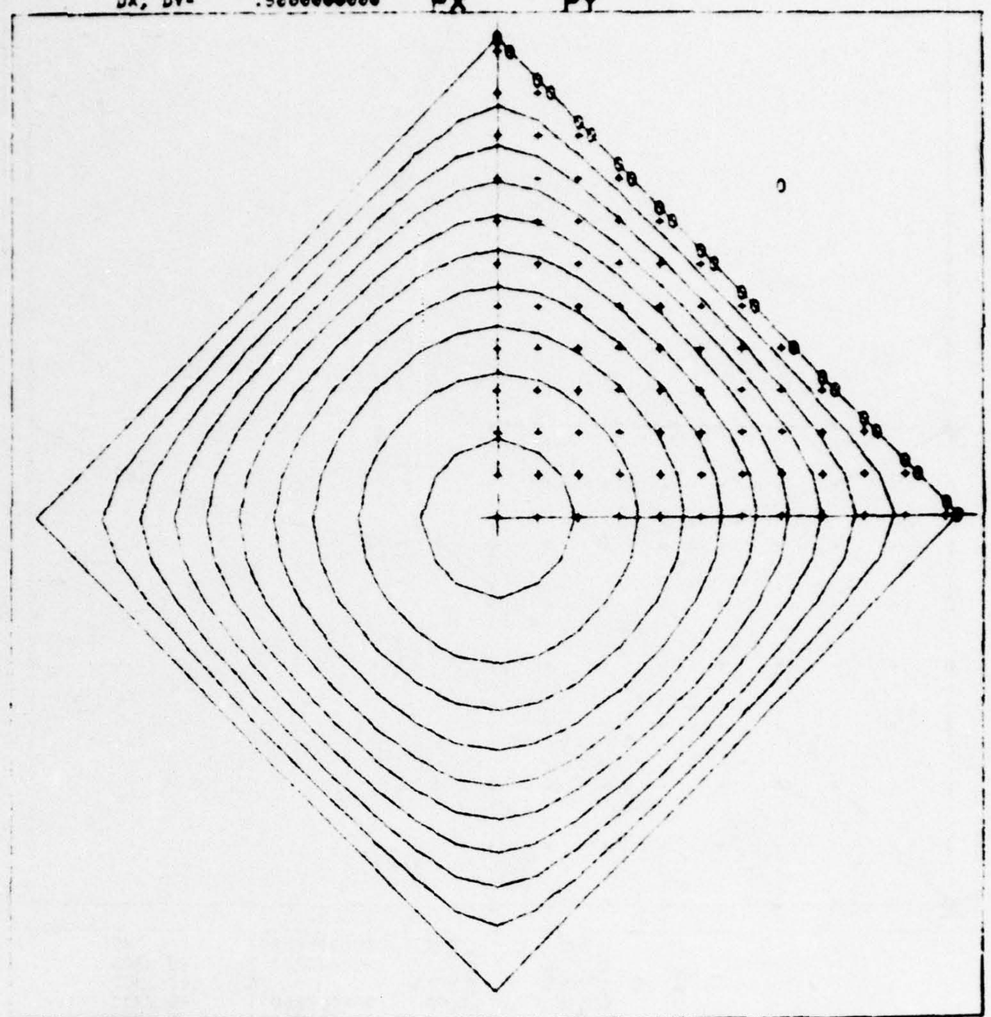
```
(C)-CONTINUE     (U)-VALUE
(M)-MODIFY DATA  (G)-RANGE
(P)-PLOT         (X)-CROSS SECTION
(N)-NEW DATA     (Z)-CROSS SECT-MIRROR
(R)-RETURN       (K)-COMB. PLOT
(E-S)END         (T)-RESTART(NODES)
                 (L)-RESTART(NO NODES)
                 (U)-MIRROR/UNMIRR

ENTER MINIMUM = 1.
ENTER MAXIMUM = 9.
ENTER NO. OF CONTOURS= 009
009
          .10000000E+01
          .20000000E+01
          .30000000E+01
          .40000000E+01
          .50000000E+01
          .60000000E+01
          .70000000E+01
          .80000000E+01
          .90000000E+01
```

CLYDE-TEK, TORSION OF SOLID SQUARE SHAFT 8 IN. (45 DEG)

```
COEF A=   1.000000000
COEF B=   1.000000000
COEF C=   0.
COEF D=  -2.000000000
DX, DY=   .5000000000
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



```
THE RANGE IS FROM     0.0000000000 TO       9.4564010051
VOLUME =      286.2882464   CROSS SECTION AREA=    63.99989436
```

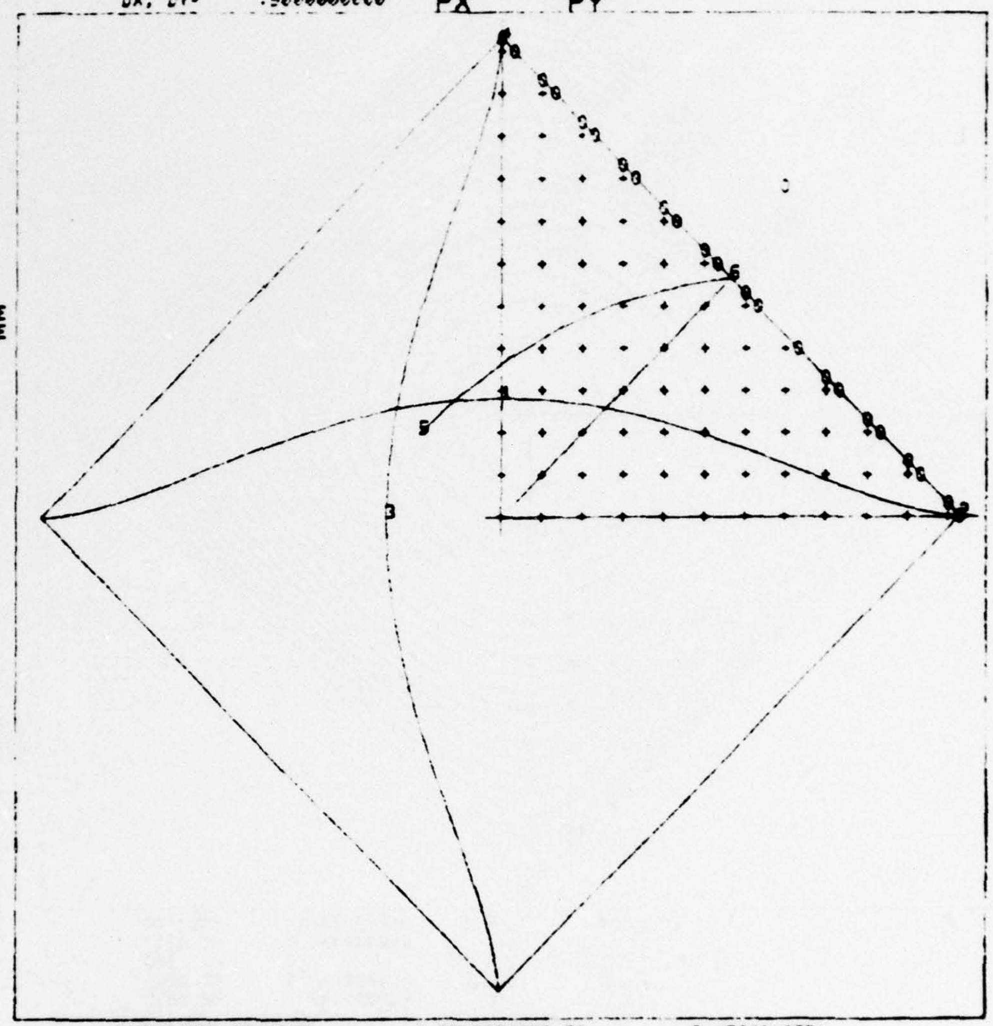
SAME SHAFT ROTATED 45° WITH 0.5 INCH GRID (DX,DY SHOULD REALLY HAVE BEEN $0.5/\sqrt{2}$). THE TORQUE RELATED VOLUME IS 286.29 CUBIC INCHES, A CHANGE OF 0.7%.

```
(C)-CONTINUE    (V)-VALUE
(M)-MODIFY DATA (G)-RANGE
(P)-PLOT        (X)-CROSS SECTION
(N)-NEW DATA    (Z)-CROSS SECT-MIRROR
(R)-RETURN      (K)-COMB. PLOT
(E-S)END        (T)-RESTART(NODES)
                (L)-RESTART(NO NODES)
                (U)-MIRROR/UNMIRR

THE RANGE AT THE CROSS SECTION GOES FROM
   0.            TO      .945639E+01
SLOPE AT 1 IS     -.24995
SLOPE AT 2 IS      .01868
THE RANGE AT THE CROSS SECTION GOES FROM
   0.            TO      .945640E+01
SLOPE AT 3 IS     -.25000
SLOPE AT 4 IS      .01878
MOVE CROSS HAIR TO 1ST PT. OF CUTTING LINE
MOVE CROSS HAIR TO 2ND PT. OF CUTTING LINE
THE RANGE AT THE CROSS SECTION GOES FROM
   0.            TO      .945640E+01
SLOPE AT 5 IS      .01059
SLOPE AT 6 IS     5.36224
```

```
CLYDE-TEK, TORSION OF SOLID SQUARE SHAFT 8 IN. (45 DEG)
   COEF A=     1.0000000000
   COEF B=     1.0000000000
   COEF C=     0.
   COEF D=    -2.0000000000
   DX, DY=     .5000000000
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$




```
THE RANGE IS FROM        0.0000000000 TO        9.4564010051
VOLUME =      286.2882464     CROSS SECTION AREA=     63.99999436
```

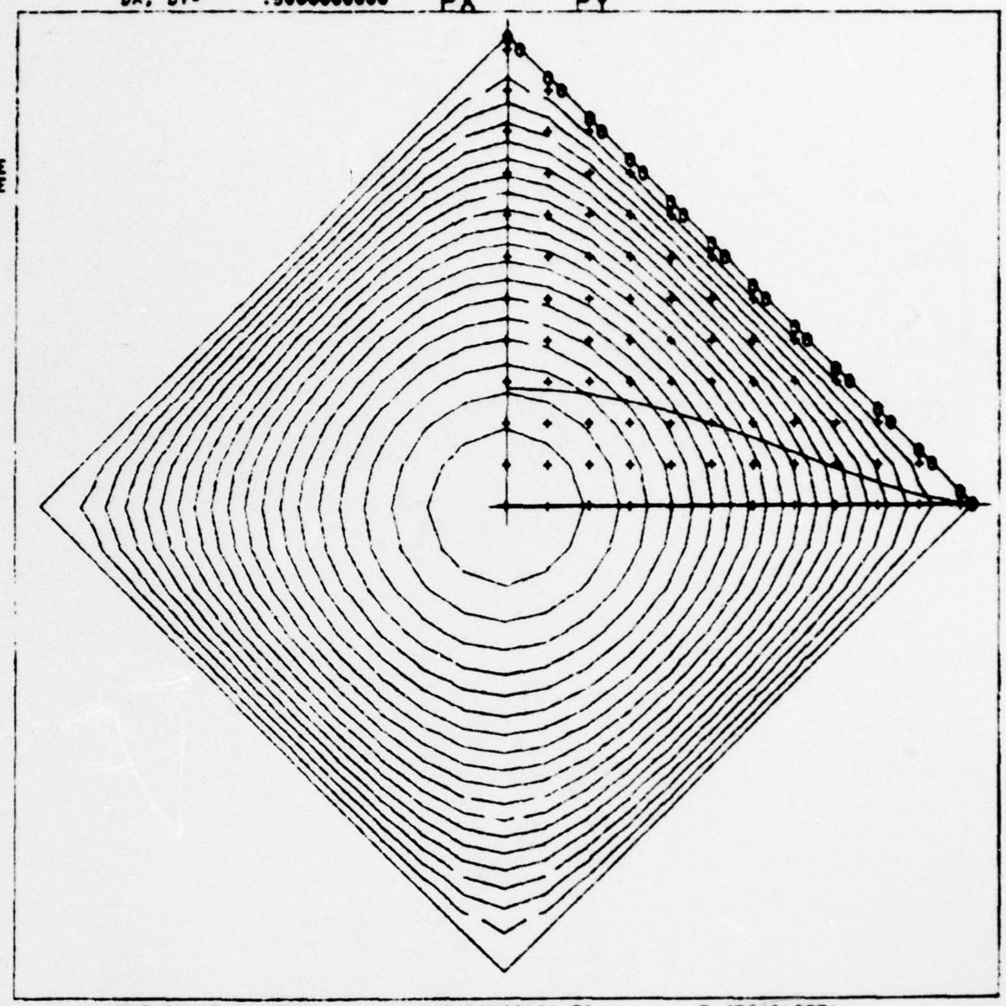
CRITICAL STRESS RELATED SLOPES ARE NOW 5.36, AT MIDDLE OF SIDES, A 9.25% CHANGE.

```
(C)-CONTINUE       (V)-VALUE
(M)-MODIFY DATA    (G)-RANGE
(P)-PLOT           (X)-CROSS SECT
(N)-NEW DATA       (K)-COMB. PLOT
(R)-RETURN         (T)-RESTART(NODES)
(E-S)END           (L)-RESTART(NO NODES)
                   (U)-MIRROR/UNMIRR

MOVE CROSS HAIR TO 1ST PT. OF CUTTING LINE
MOVE CROSS HAIR TO 2ND PT. OF CUTTING LINE
THE RANGE AT THE CROSS SECTION GOES FROM
   0.            TO        .945307E+01
ENTER MINIMUM - 0.50
ENTER MAXIMUM - 9.0
ENTER NO. OF CONTOURS- 018
018
                   .50000000E+00
                   .10000000E+01
                   .15000000E+01
                   .20000000E+01
                   .25000000E+01
                   .30000000E+01
                   .35000000E+01
                   .40000000E+01
                   .45000000E+01
                   .50000000E+01
                   .55000000E+01
                   .60000000E+01
                   .65000000E+01
                   .70000000E+01
                   .75000000E+01
                   .80000000E+01
                   .85000000E+01
                   .90000000E+01
```

```
CLYDE-TEK, TORSION OF SOLID SQUARE SHAFT 8 IN. (45 DEG)
   COEF A-     1.000000000
   COEF B-     1.000000000
   COEF C-     0.
   COEF D-    -2.000000000
   DX, DY-     .5000000000
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



```
THE RANGE IS FROM          0.0000000000 TO         9.4564010051
VOLUME -        286.2882464     CROSS SECTION AREA-     63.99998436
```

HERE'S A GRID SIZE COMPARISON.
TORQUE RELATED VOLUME, WITH 0.5
INCH GRID, IS 286.29.

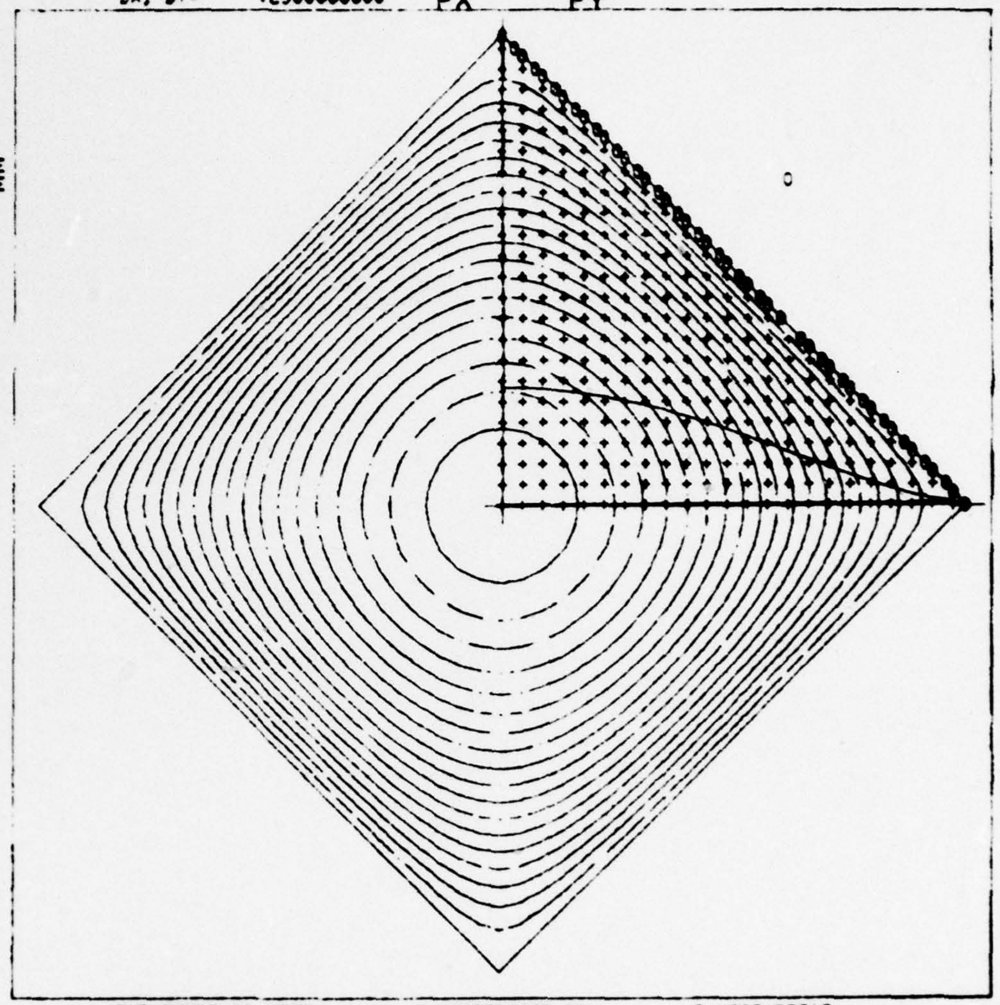
```
(C)-CONTINUE        (V)-VALUE
(M)-MODIFY DATA     (G)-RANGE
(P)-PLOT            (X)-CROSS SECT
(N)-NEW DATA        (K)-COMB. PLOT
(P)-RETURN          (T)-RESTART(NODES)
(E-S)END            (L)-RESTART(NO NODES)
                    (U)-MIRROR/UNMIRR

MOVE CROSS HAIR TO 1ST PT. OF CUTTING LINE
MOVE CROSS HAIR TO 2ND PT. OF CUTTING LINE
THE RANGE AT THE CROSS SECTION GOES FROM
   0.            TO         .943503E+01
ENTER MINIMUM - 0.50
ENTER MAXIMUM - 9.00
ENTER NO. OF CONTOURS- 018
018
                 .50000000E+00
                 .10000000E+01
                 .15000000E+01
                 .20000000E+01
                 .25000000E+01
                 .30000000E+01
                 .35000000E+01
                 .40000000E+01
                 .45000000E+01
                 .50000000E+01
                 .55000000E+01
                 .60000000E+01
                 .65000000E+01
                 .70000000E+01
                 .75000000E+01
                 .80000000E+01
                 .85000000E+01
                 .90000000E+01
```

CLYDE-TEK. TORSION OF SOLID SQUARE SHAFT 8 IN. (45 DEG)

```
COEF A-    1.000000000
COEF B-    1.000000000
COEF C-    0.
COEF D-   -2.000000000
DX, DY-    .2500000000
```

$$A\frac{P^2Q}{PX^2} + B\frac{P^2Q}{PY^2} = D$$



```
THE RANGE IS FROM       0.0000000000 TO        9.4367187612
VOLUME -      287.6000028     CROSS SECTION AREA-     63.99990304
```

TORQUE RELATED VOLUME, WITH 0.25 INCH GRID, IS 287.61, A 0.46% CHANGE.

APPENDICIES

A. OTHER APPLICATIONS

B. MATHEMATICAL MODEL

C. THINGS TO COME

D. AUTHORS' CONTROL CARDS

E. REFERENCES

F. UPDATE SUBSCRIPTION SERVICE CARD

A. OTHER APPLICATIONS

MONITORING EARTH'S ELECTROSTATIC FIELD

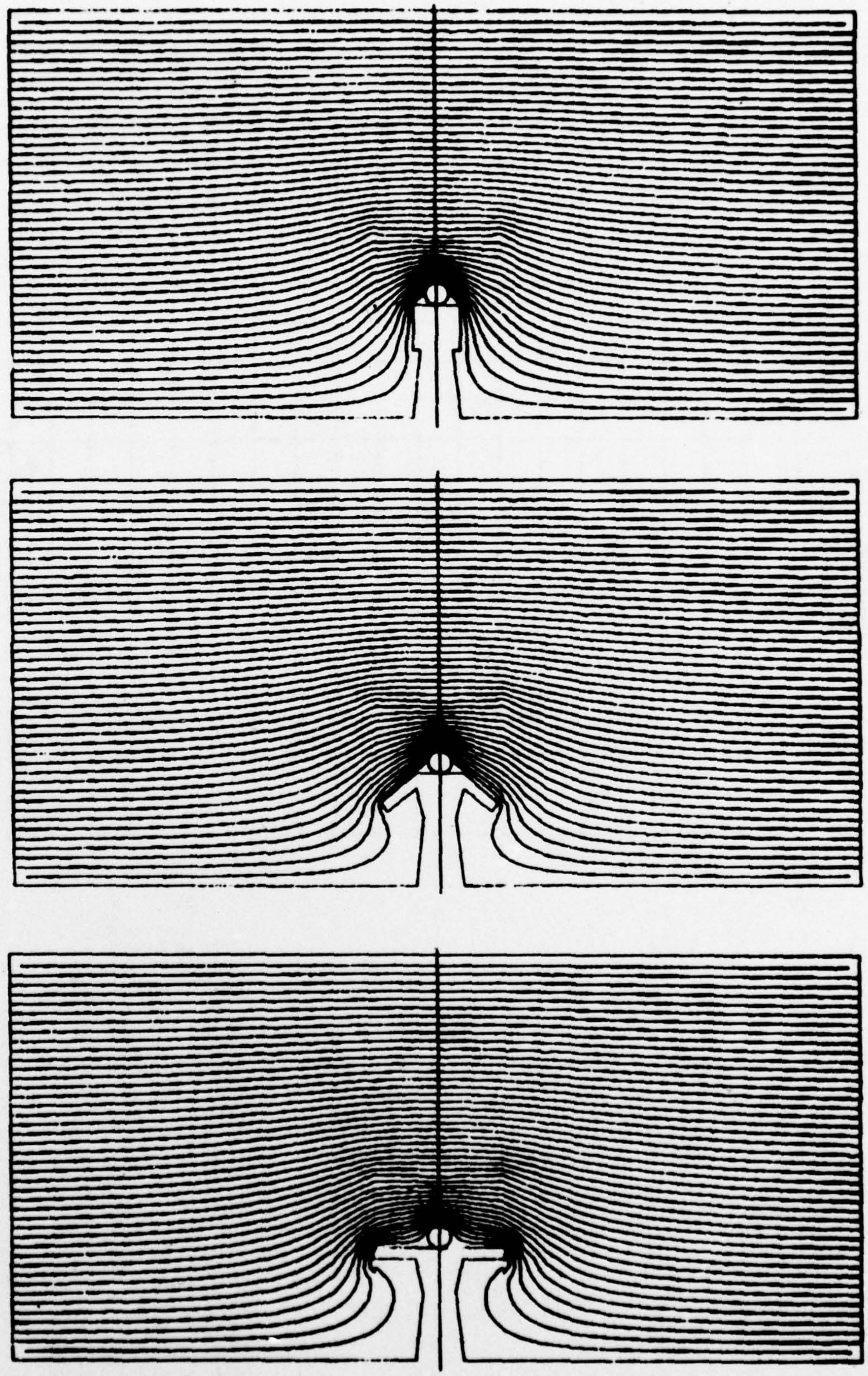
An evolutionary version of the CLYDE program has been used to investigate the feasibility of portable anti-intrusion devices and autopilot sensors. Both are based upon the same principle: the atmosphere being a giant capacitor. The earth is negatively charged and the air above positively charged with voltage layers ranging from zero at the surface ground to about 350,000 volts at the top of the atmospheric layer. The voltage gradient is greatest at sea level (50 volts/foot) and decreases with altitude. The current is too small to sense, but the voltage layers, nevertheless, do exist, and can be measured.

Anti-Intrusion Detectors:

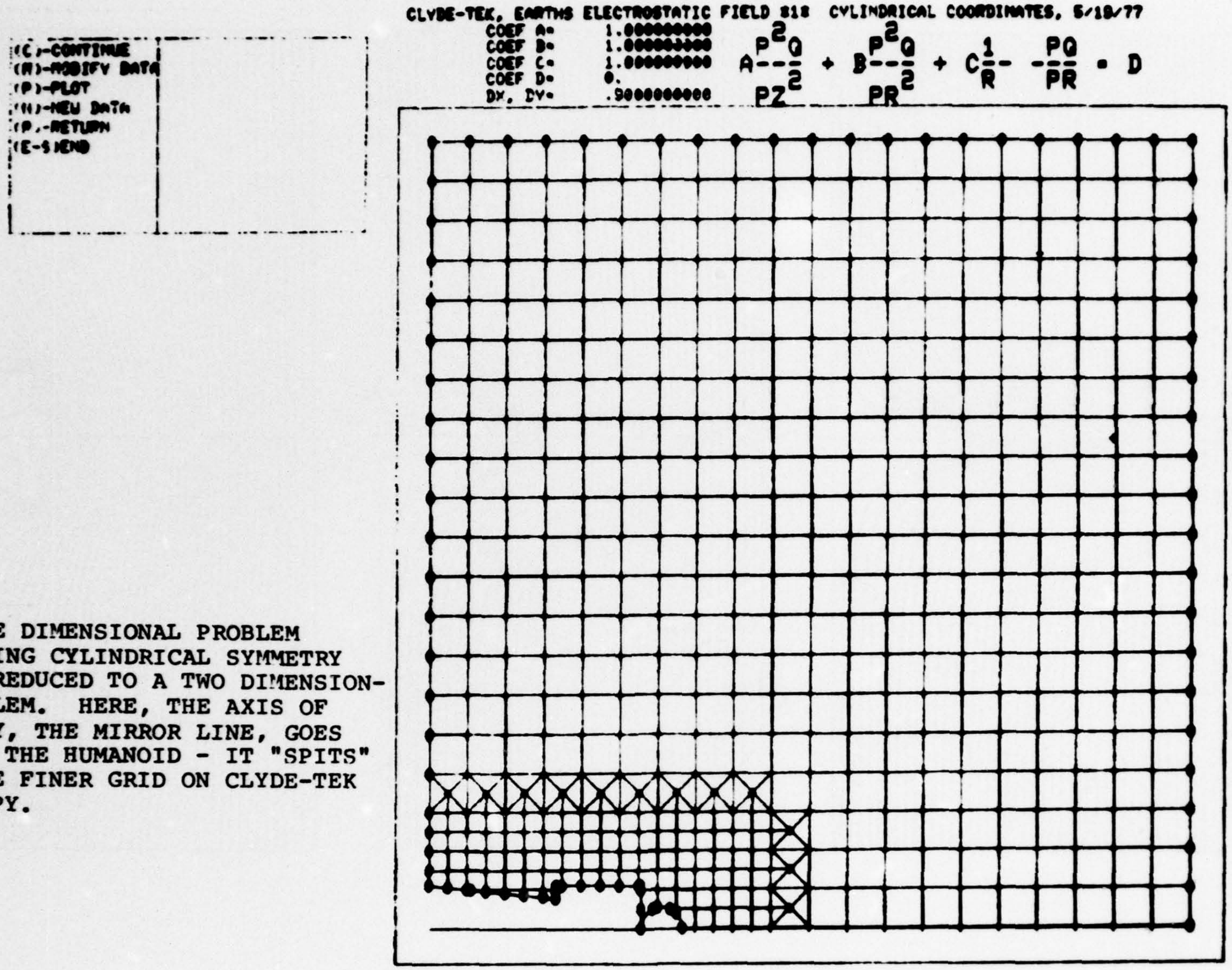
A man standing in an open field distorts the earth's electrostatic field. Houses and boulders also distort the field, but they are stationary while an intruder must normally move (to intrude effectively). The anti-intrusion device is designed to monitor the rate of field distortion caused by the moving intruder.

Autopilot Sensor:

Roll and pitch sensors mounted on wing tips and near nose and tail of the aircraft read different voltage signals when flight deviates from the horizontal plane. Pairs of these signals (wing tips, nose and tail) fed into differential voltmeters drive the roll and pitch servos to correct the flight. The system works well, so far, in nonmetallic models in good weather.



HUMANOID DISTORTING THIRD PLANET'S ELECTROSTATIC FIELD.



A THREE DIMENSIONAL PROBLEM POSSESSING CYLINDRICAL SYMMETRY MAY BE REDUCED TO A TWO DIMENSIONAL PROBLEM. HERE, THE AXIS OF SYMMETRY, THE MIRROR LINE, GOES THROUGH THE HUMANOID - IT "SPITS" IT. NOTE FINER GRID ON CLYDE-TEK HARD COPY.

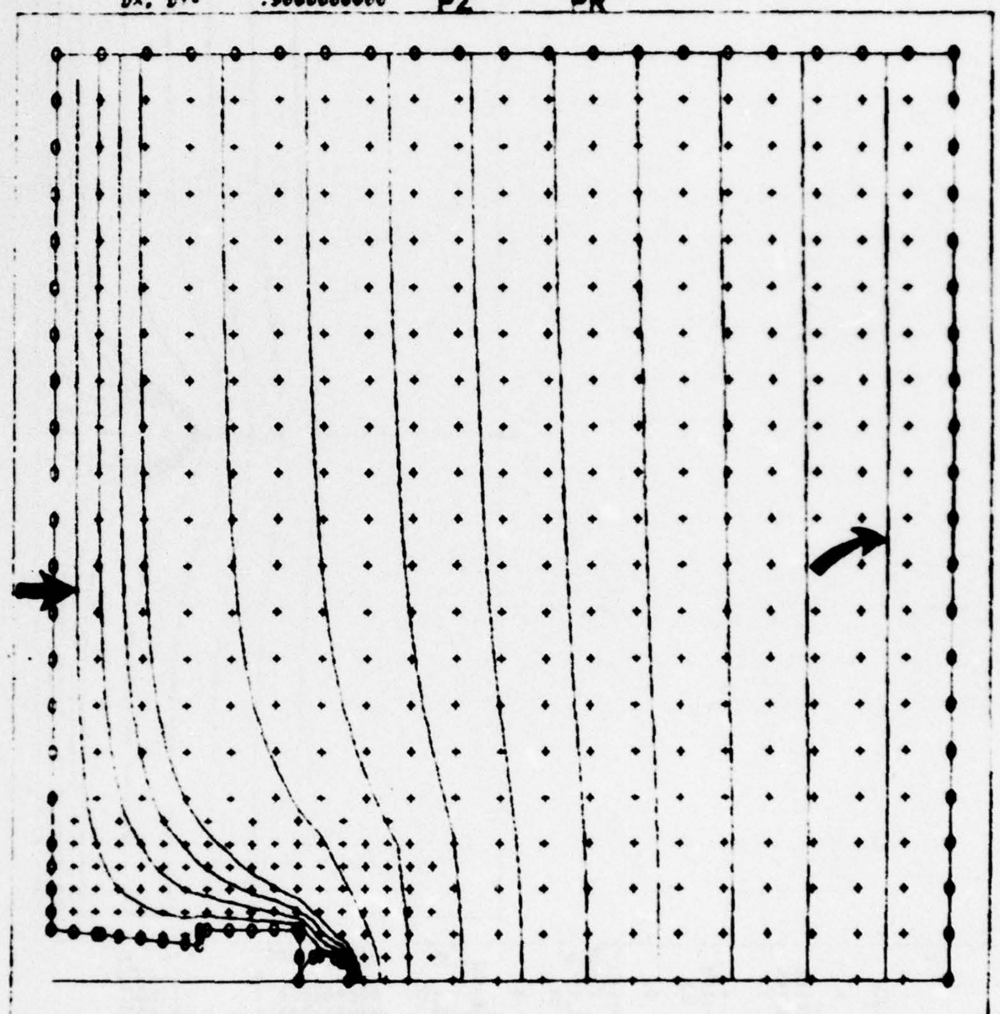
```
(C)-CONTINUE       (V)-VALUE
(M)-MODIFY DATA    (G)-RANGE
(P)-PLOT           (X)-CROSS SECTION
(N)-NEW DATA       (Z)-CROSS SECT-MIRROR
(P,-RETURN         (K)-COMB. PLOT
(E-S)END           (T)-RESTART(NODES)
                   (L)-RESTART(NC NODES)
                   (U)-MIRROR/UNMIRR

ENTER MINIMUM : 25.0
ENTER MAXIMUM : 75.0
ENTER NO. OF CONTOURS: 003
003
                 .2500000E+02
                 .5000000E+02
                 .7500000E+02
ENTER MINIMUM : 100.
ENTER MAXIMUM : 1000.
ENTER NO. OF CONTOURS: 010
010
                 .1000000E+03
                 .2000000E+03
                 .3000000E+03
                 .4000000E+03
                 .5000000E+03
                 .6000000E+03
                 .7000000E+03
                 .8000000E+03
                 .9000000E+03
                 .1000000E+04
```

CLYDE-TEK, EARTHS ELECTROSTATIC FIELD #18 CYLINDRICAL COORDINATES, 5/19/77

```
COEF A:   1.000000000
COEF B:   1.000000000
COEF C:   1.000000000
COEF D:   0.
DX, DY:   .3000000000
```

$$A\frac{P^2Q}{PZ^2} + B\frac{P^2Q}{PR^2} + C\frac{1}{R}\frac{PQ}{PR} = D$$



THE RANGE IS FROM 0.0000000000 TO 1000.000000000

CONTOUR LINES OF CONSTANT (ELECTROSTATIC) VOLTAGE. ARMS DOWN.

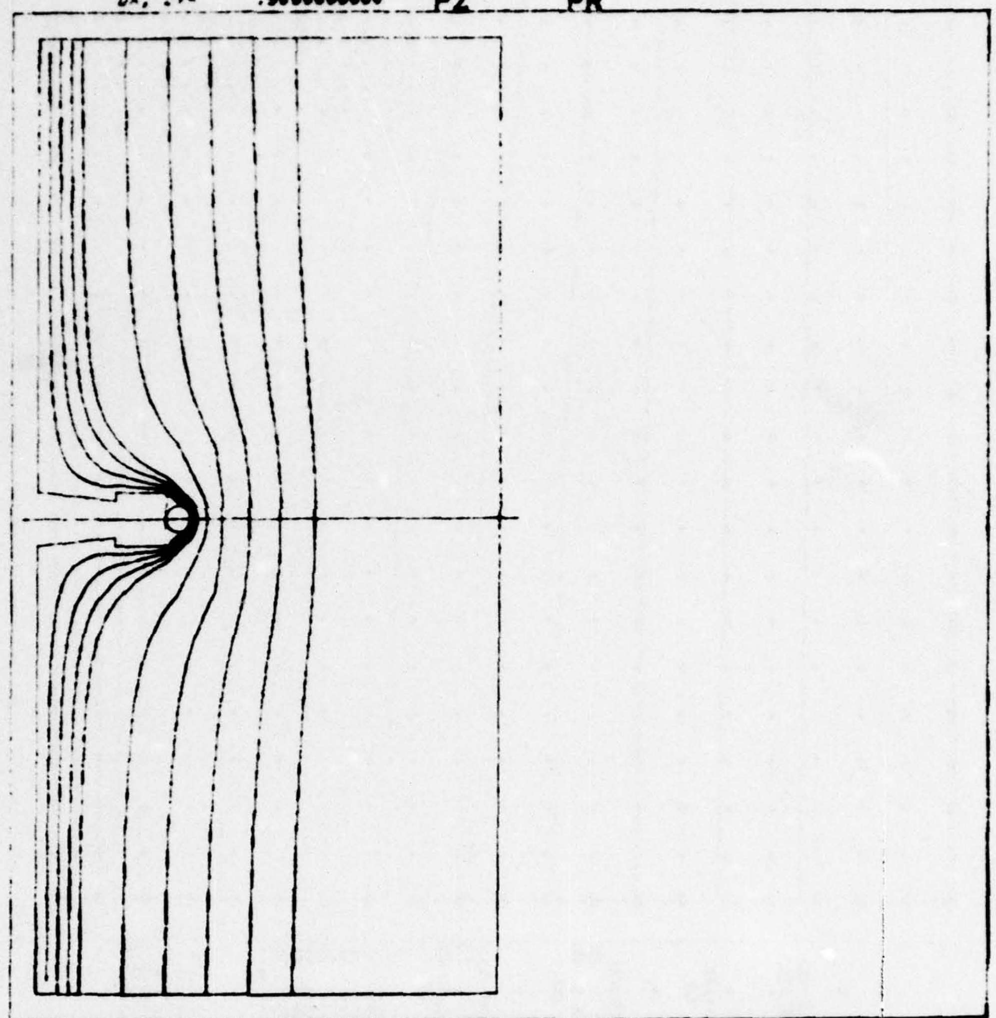
CLYDE-TEK, EARTHS ELECTROSTATIC FIELD #18 CYLINDRICAL COORDINATES, 5/19/77

```
COEF A=    1.000000000
COEF B=    1.000000000
COEF C=    1.000000000
COEF D=    0.
DX, DY=     .9000000000
```

$$A\frac{P^2Q}{PZ^2} + B\frac{P^2Q}{PR^2} + C\frac{1}{R}\frac{PQ}{PR} = D$$

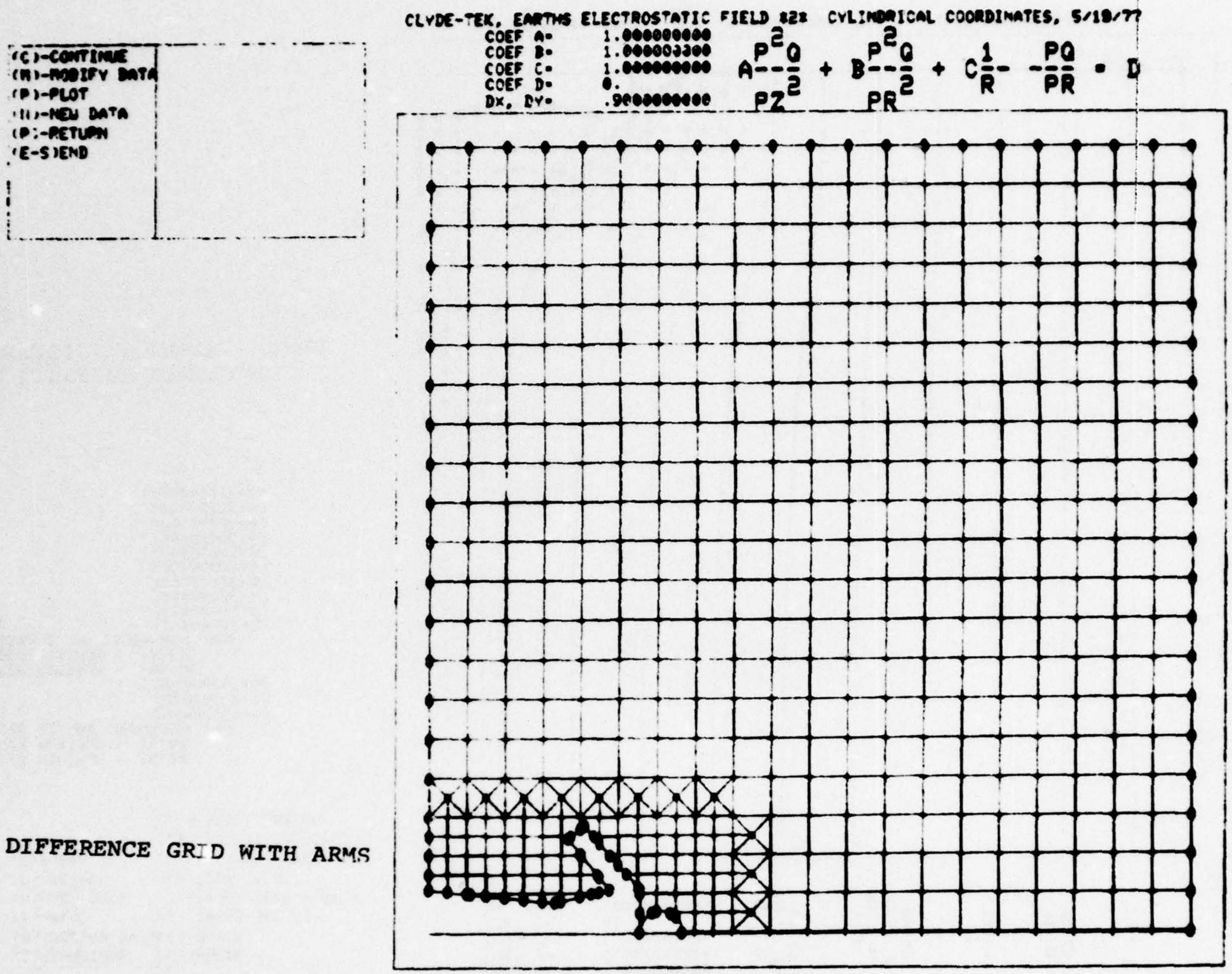
```
(C)-CONTINUE       (V)-VALUE
(M)-MODIFY DATA    (G)-RANGE
(P)-PLOT           (X)-CROSS SECTION
(N)-NEW DATA       (Z)-CROSS SECT-MIRROR
(R)-RETURN         (K)-COMB. PLOT
(E-S)END           (T)-RESTART(NODES)
                   (L)-RESTART(NO NODES)
                   (U)-MIRROR/UNMIRR

ENTER MINIMUM = 25.00
ENTER MAXIMUM = 75.00
ENTER NO. OF CONTOURS= 003
003
                  .25000000E+02
                  .50000000E+02
                  .75000000E+02
ENTER MINIMUM = 100.00
ENTER MAXIMUM = 600.00
ENTER NO. OF CONTOURS= 006
006
                  .10000000E+03
                  .20000000E+03
                  .30000000E+03
                  .40000000E+03
                  .50000000E+03
                  .60000000E+03
```



THE RANGE IS FROM 0.0000000000 TO 1000.0000000000

FULL MIRRORED VIEW WITH ARMS DOWN.



FINITE DIFFERENCE GRID WITH ARMS AT 45°.

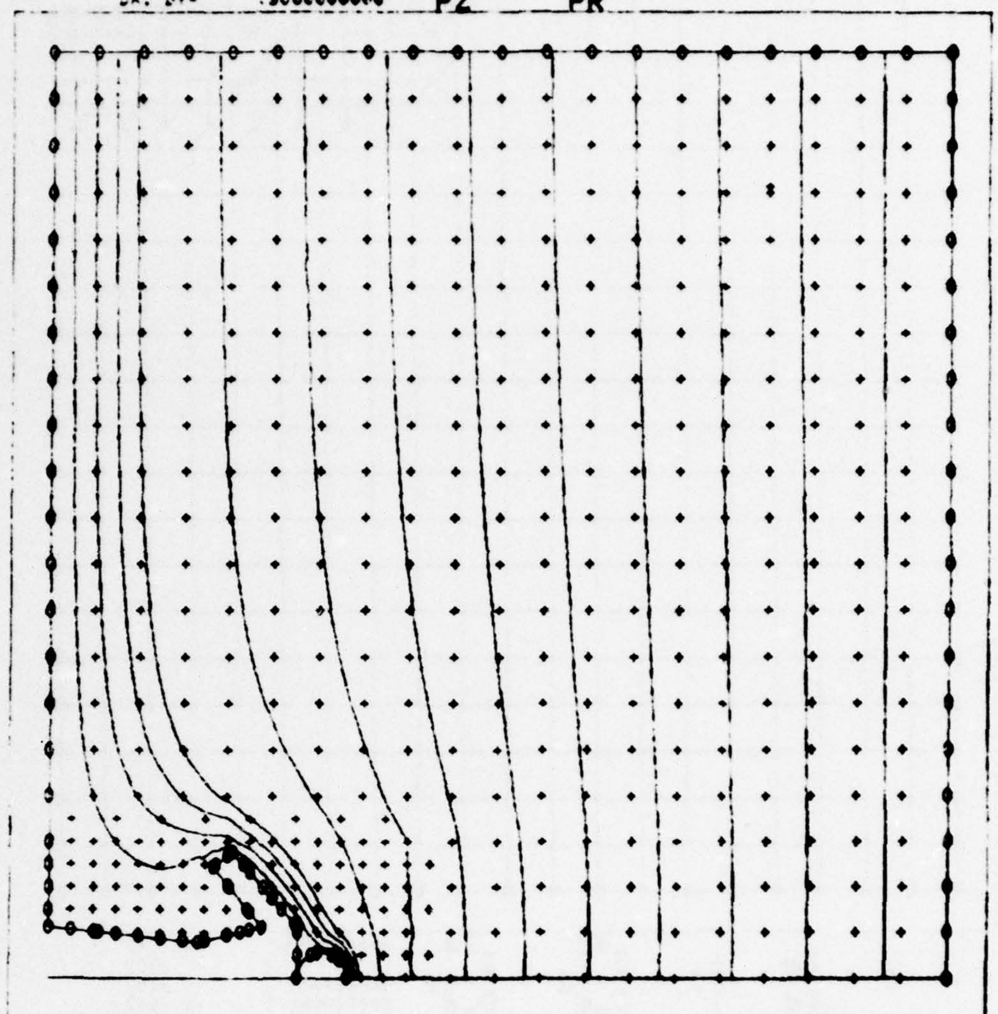
```
(C)-CONTINUE     (V)-VALUE
(M)-MODIFY DATA  (G)-RANGE
(P)-PLOT         (X)-CROSS SECTION
(N)-NEW DATA     (Z)-CROSS SECT-MIRROR
(F)-RETURN       (K)-COMB. PLOT
E-S)END          (T)-RESTART(NODES)
                 (L)-RESTART(NO NODES)
                 (U)-MIRROR/UNMIRR

ENTER MINIMUM : 25.00
ENTER MAXIMUM : 75.00
ENTER NO. OF CONTOURS: 003
003
           .25000000E+02
           .50000000E+02
           .75000000E+02
ENTER MINIMUM : 100.00
ENTER MAXIMUM : 1000.0
ENTER NO. OF CONTOURS: 010
010
           .10000000E+03
           .20000000E+03
           .30000000E+03
           .40000000E+03
           .5[illegible]
           .6[illegible]
           .7[illegible]
           .8[illegible]
           .9[illegible]
           .1[illegible]E+04
```

CLYDE-TEK, EARTHS ELECTROSTATIC FIELD #28 CYLINDRICAL COORDINATES, 5/19/77

```
COEF A:   1.000000000
COEF B:   1.000000000
COEF C:   1.000000000
COEF D:   0.
DX, DY:   .9000000000
```

$$A\frac{P^2Q}{PZ^2} + B\frac{P^2Q}{PR^2} + C\frac{1}{R} - \frac{PQ}{PR} = D$$



THE RANGE IS FROM 0.0000000000 TO 1000.0000000000

CONTOUR LINES OF CONSTANT (ELECTROSTATIC) VOLTAGE. ARMS AT 45°.

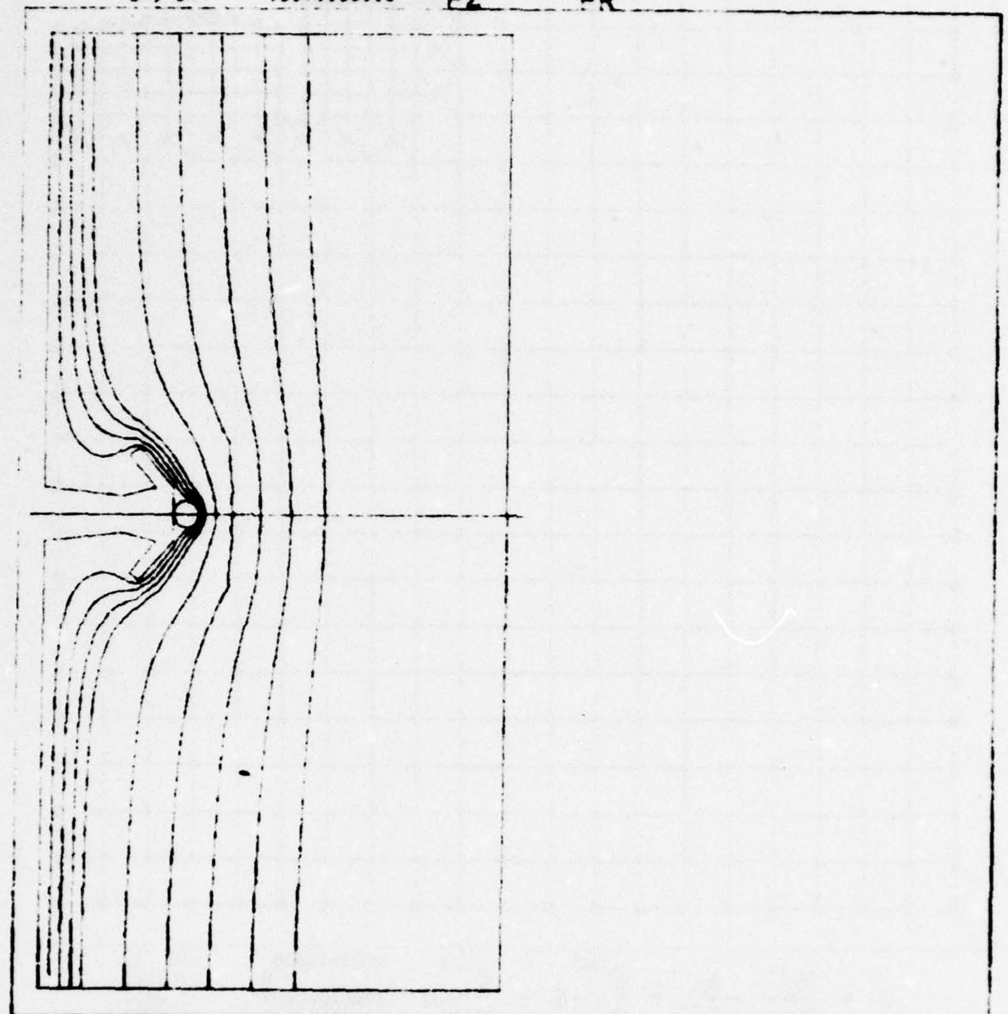
```
(C)-CONTINUE       (V)-VALUE
(M)-MODIFY DATA    (G)-RANGE
(P)-PLOT           (X)-CROSS SECTION
(N)-NEW DATA       (Z)-CROSS SECT-MIRROR
(R)-RETURN         (K)-COMB. PLOT
(E-S)END           (T)-RESTART(NODES)
                   (L)-RESTART(NO NODES)
                   (U)-MIRROR/UNMIRR

ENTER MINIMUM = 25.00
ENTER MAXIMUM = 75.00
ENTER NO. OF CONTOURS= 003
003
                  .25000000E+02
                  .50000000E+02
                  .75000000E+02
ENTER MINIMUM = 100.00
ENTER MAXIMUM = 600.00
ENTER INC. OF CONTOURS= 006
006
                  .10000000E+03
                  .20000000E+03
                  .30000000E+03
                  .40000000E+03
                  .50000000E+03
                  .60000000E+03
```

CLYDE-TEK, EARTHS ELECTROSTATIC FIELD 828 CYLINDRICAL COORDINATES, 5/19/77

```
COEF A=    1.000000000
COEF B=    1.000000000
COEF C=    1.000000000
COEF D=    0.
DX, DY=     .5000000000
```

$$A\frac{P^2Q}{PZ^2} + B\frac{P^2Q}{PR^2} + C\frac{1}{R} - \frac{PQ}{PR} = D$$



THE RANGE IS FROM 0.0000000000 TO 1000.0000000000

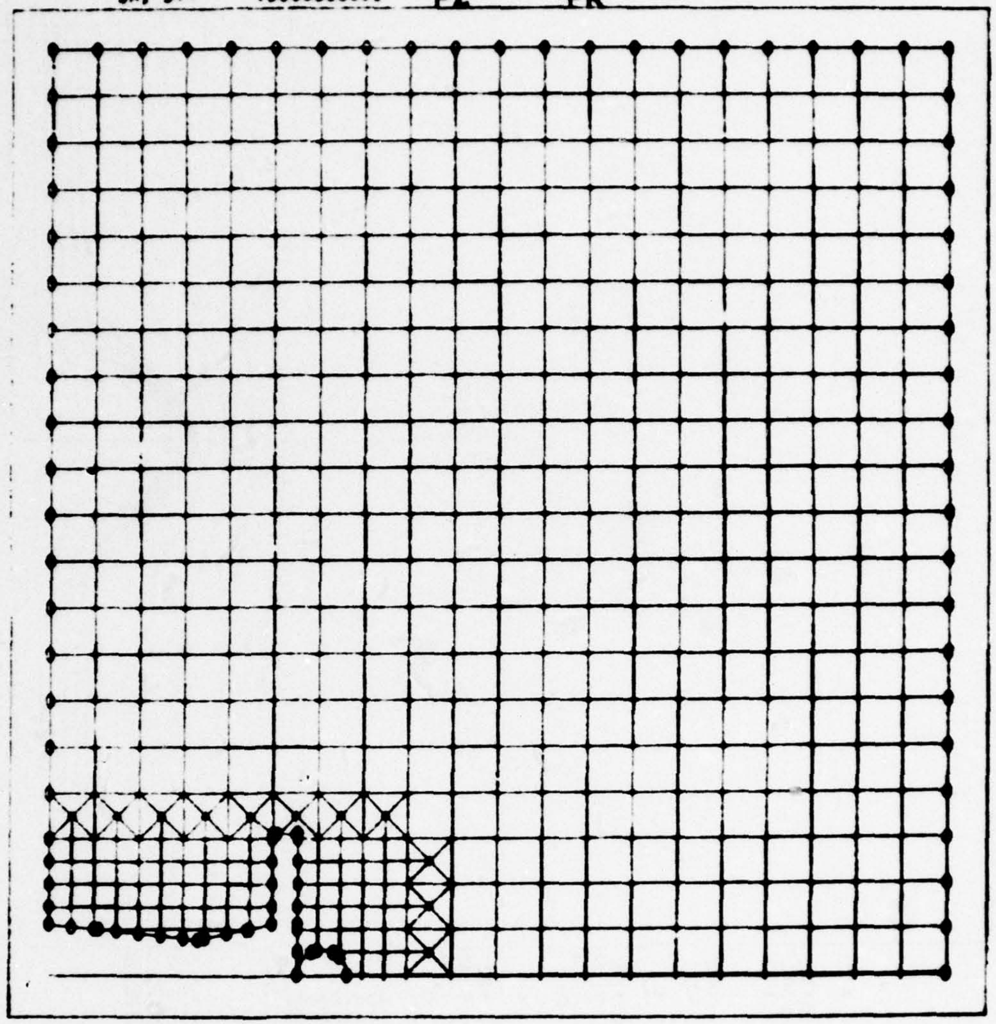
FULL MIRRORED VIEW WITH ARMS AT 45°.

CLYDE-TEK, EARTHS ELECTROSTATIC FIELD #38 CYLINDRICAL COORDINATES, 5/18/77

COEF A= 1.000000000
COEF B= 1.000000000
COEF C= 1.000000000
COEF D= 0.
DX, DY= .9000000000

$$A\frac{P^2Q}{PZ^2} + B\frac{P^2Q}{PR^2} + C\frac{1}{R}\frac{PQ}{PR} = D$$

(C)-CONTINUE
(M)-MODIFY DATA
(P)-PLOT
(N)-NEW DATA
(R)-RETURN
(E-S)END



FINITE DIFFERENCE GRID WITH ARMS AT 90°.

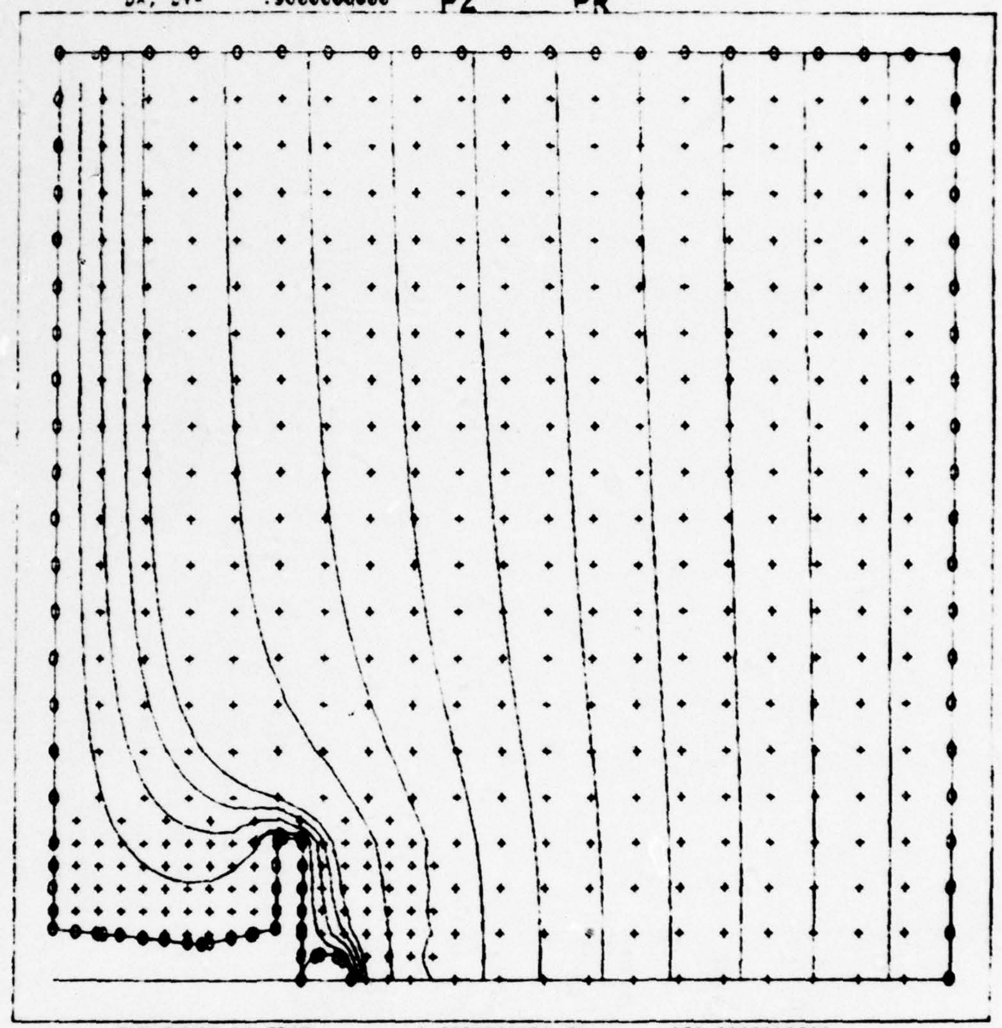
```
(C)-CONTINUE       (V)-VALUE
(M)-MODIFY DATA    (G)-RANGE
(P)-PLOT           (X)-CROSS SECTION
(N)-NEW DATA       (Z)-CROSS SECT-MIRROR
(R)-RETURN         (K)-COMB. PLOT
(E-S)END           (T)-RESTART(NODES)
                   (L)-RESTART(NO NODES)
                   (U)-MIRROR/UNMIRR

ENTER MINIMUM - 25.00
ENTER MAXIMUM - 75.00
ENTER NO. OF CONTOURS- 003
003
                    .25000000E+02
                    .50000000E+02
                    .75000000E+02
ENTER MINIMUM - 100.00
ENTER MAXIMUM - 1000.0
ENTER NO. OF CONTOURS- 010
010
                    .10000000E+03
                    .20000000E+03
                    .30000000E+03
                    .40000000E+03
                    .50000000E+03
                    .60000000E+03
                    .70000000E+03
                    .80000000E+03
                    .90000000E+03
                    .10000000E+04
```

CLYDE-TEK, EARTHS ELECTROSTATIC FIELD 838 CYLINDRICAL COORDINATES, 5/19/77

```
COEF A-    1.000000000
COEF B-    1.000000000
COEF C-    1.000000000
COEF D-    0.
DX, DY-    .9000000000
```

$$A\frac{P^2Q}{PZ^2} + B\frac{P^2Q}{PR^2} + C\frac{1}{R} - \frac{PQ}{PR} = D$$



THE RANGE IS FROM 0.0000000000 TO 1000.0000000000

CONTOUR LINES OF CONSTANT (ELECTROSTATIC) VOLTAGE. ARMS AT 90°.

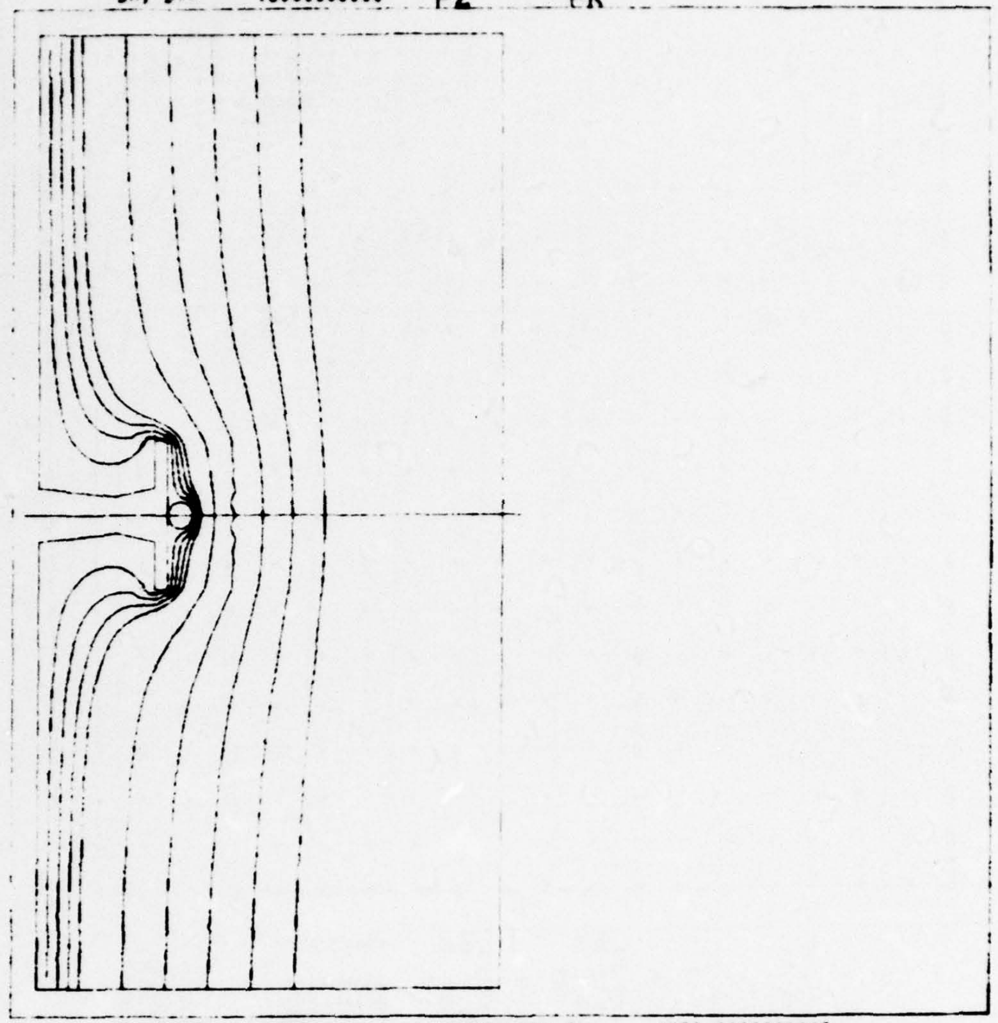
```
(C)-CONTINUE       (U)-VALUE
(M)-MODIFY DATA    (G)-RANGE
(P)-PLOT           (X)-CROSS SECTION
(N)-NEW DATA       (Z)-CROSS SECT-MIRROR
(R)-RETURN         (K)-COMB. PLOT
(E-S)END           (T)-RESTART(NODES)
                   (L)-RESTART(NO NODES)
                   (U)-MIRROR/UNMIRR

ENTER MINIMUM : 25.00
ENTER MAXIMUM : 75.00
ENTER NO. OF CONTOURS- 003
00300
                   .25000000E+02
                   .50000000E+02
                   .75000000E+02
ENTER MINIMUM : 100.00
ENTER MAXIMUM : 600.00
ENTER NO. OF CONTOURS- 006
006
                   .10000000E+03
                   .20000000E+03
                   .30000000E+03
                   .40000000E+03
                   .50000000E+03
                   .60000000E+03
```

CLYDE-TEK, EARTHS ELECTROSTATIC FIELD #3* CYLINDRICAL COORDINATES, 5/19/77

```
COEF A=    1.000000000
COEF B=    1.000000000
COEF C=    1.000000000
COEF D=    0.
DX, DY=    .9000000000
```

$$A\frac{P^2Q}{PZ^2} + B\frac{P^2Q}{PR^2} + C\frac{1}{R}\frac{PQ}{PR} = D$$



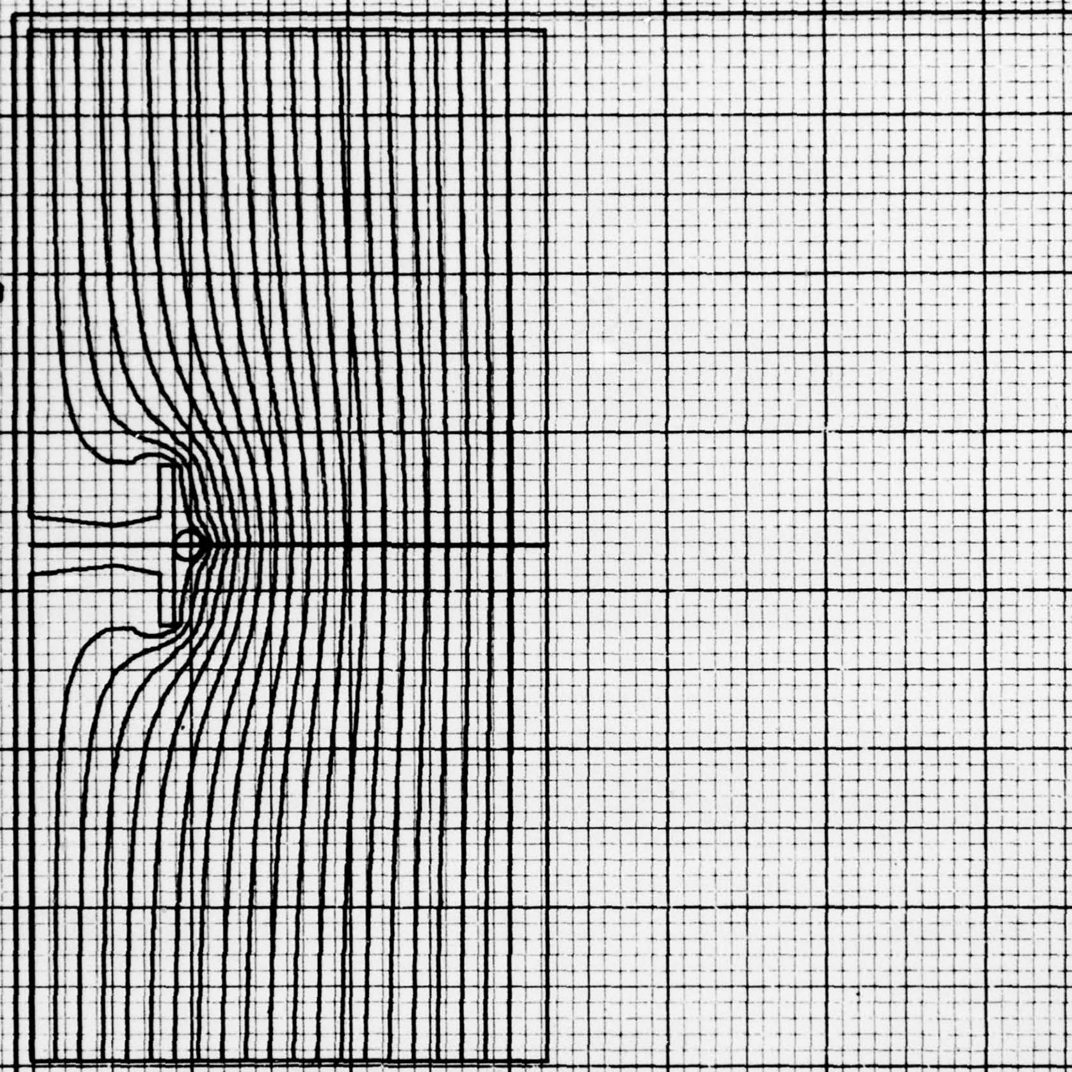
THE RANGE IS FROM 0.0000000000 TO 1080.0000000000

FULL MIRRORED VIEW WITH ARMS AT 90 .

$$A\frac{P^2Q}{PZ^2} + B\frac{P^2Q}{PR^2} + C\frac{1}{R}\,\frac{PQ}{PR} = 0$$

COEF A=	1.0000000000
COEF B=	1.0000000000
COEF C=	1.0000000000
COEF D=	0.0000000000
DX,DY =	.9000000000
RANGE IS	0.000000 TO 1000.000000
CONTOUR VALUE	50.0000000
CONTOUR VALUE	100.000000
CONTOUR VALUE	150.000000
CONTOUR VALUE	200.000000
CONTOUR VALUE	250.000000
CONTOUR VALUE	300.000000
CONTOUR VALUE	350.000000
CONTOUR VALUE	400.000000
CONTOUR VALUE	450.000000
CONTOUR VALUE	500.000000
CONTOUR VALUE	550.000000
CONTOUR VALUE	600.000000
CONTOUR VALUE	650.000000
CONTOUR VALUE	700.000000
CONTOUR VALUE	750.000000
CONTOUR VALUE	800.000000
CONTOUR VALUE	850.000000
CONTOUR VALUE	900.000000
CONTOUR VALUE	950.000000
CONTOUR VALUE	1000.00000

CALCOMP PLOT GENERATED BY CLYDE-BATCH.



CLYDE- EARTHS ELECTROSTATIC FIELD #3# CYLINDRICAL COORDINATES, 5/19/77

PUNCHED CARD CLYDE-TEK INPUT
FOR STEPPED AND GROOVED CIRCULAR
SHAFT.

IBM

GX28-7327-6 U/M 050**
Printed in U.S.A.

PROGRAM: TORSION OF GROOVED & STEPPED
PROGRAMMER: SHAFT (CYLINDRICAL COORDINATES)

PUNCHING INSTRUCTIONS | GRAPHIC | PUNCH | PAGE OF | CARD ELECTRO NUMBER*

STATEMENT NUMBER	CONT	FORTRAN STATEMENT (cols 7–10)	(11–15)	(16–20)	(21–25)	(31–35)	(41–45)	IDENTIFICATION SEQUENCE
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2	SL		10.0		1.0	10.0	2.0	
		-7.0		-7.0				
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		1000.0		1000.0				
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[illegible]								
		1000.0		1000.0				
8	SL		3.0		3.0	3.0	6.0	
		1000.0		1000.0				
[illegible]						[illegible]	6.0	
10	[illegible]					[illegible]	0.0	
		1000.0		1000.0				
11	SL		0.0		0.0	10.0	0.0	
		0.0		0.0				

SHAFT TORSION (CYLINDRICAL COORDINATES)

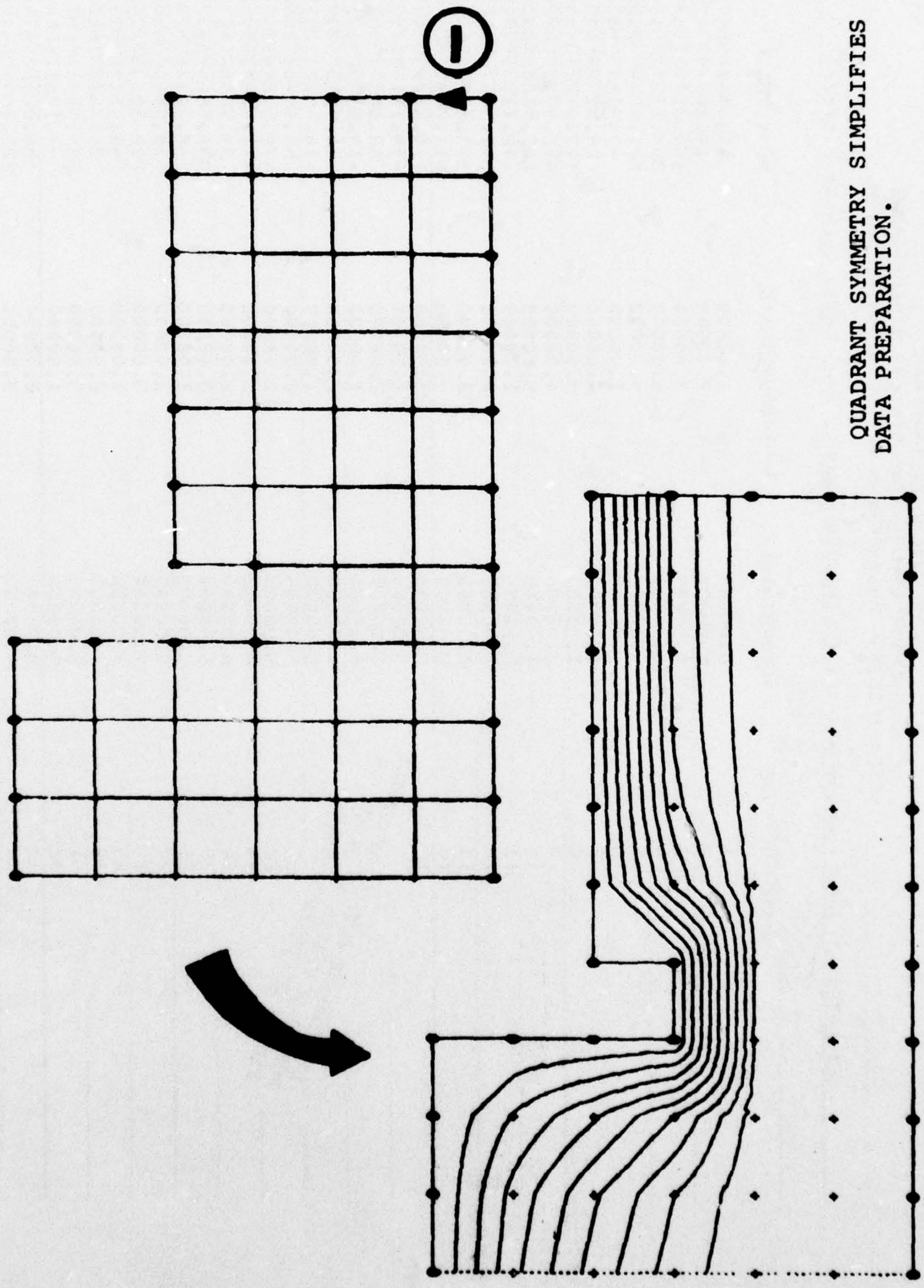
*A standard card form, IBM electro 888157, is available for punching statements from this form

**Number of forms per pad may vary slightly

CLYDE-TEK,STEPPED + GROOVED SHAFT,CYLINDRICAL COORD. R=4. DX=1. DEL-SQ=0. 6/1/77

COEF A= 1.000000000
COEF B= 1.000000000
COEF C= -3.000000000
COEF D= 0.
DX, DY= 1.000000000

$$A\frac{P^2Q}{PZ^2} + B\frac{P^2Q}{PR^2} + C\frac{1}{R}\frac{PQ}{PR} = D$$



QUADRANT SYMMETRY SIMPLIFIES DATA PREPARATION.

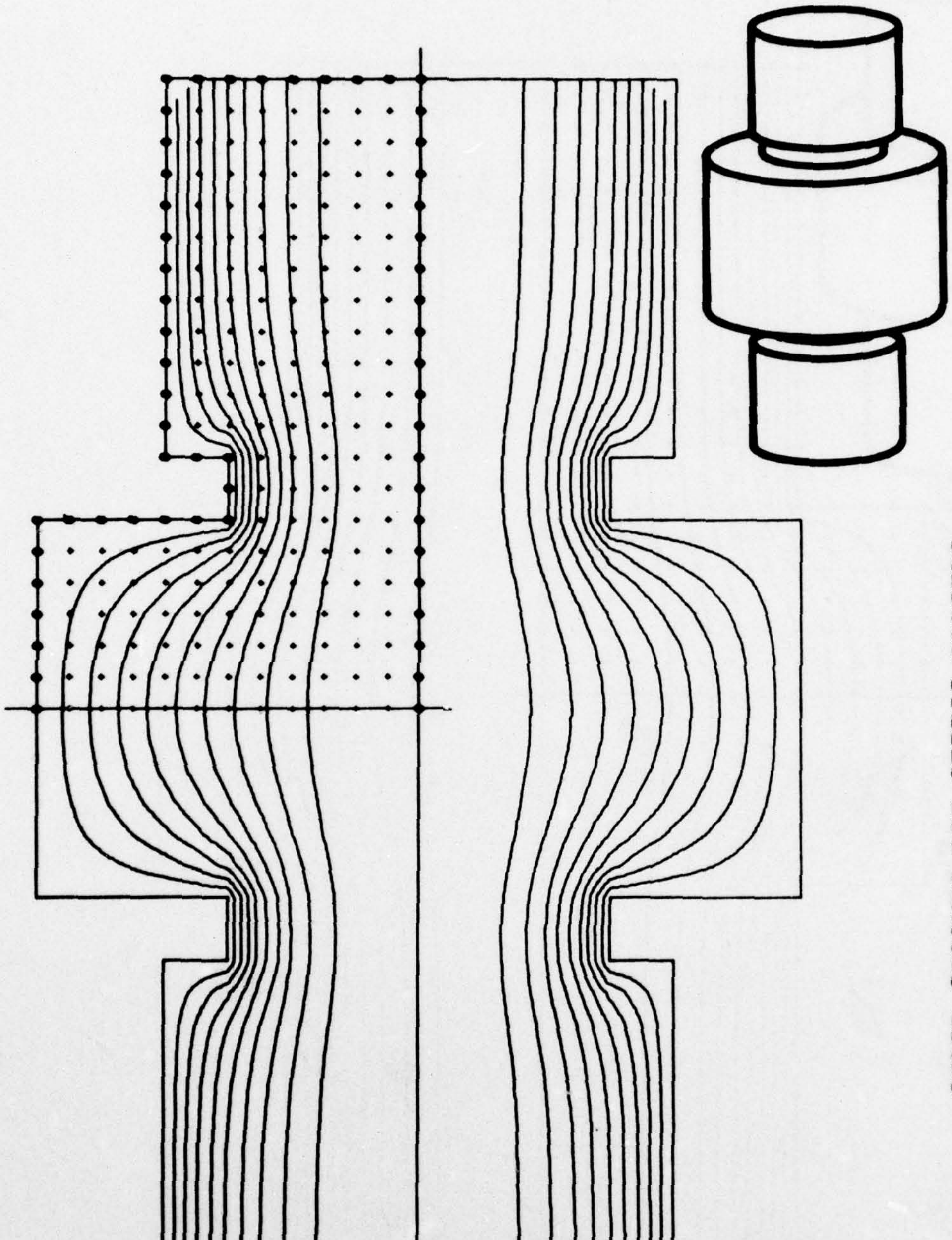
DEVELOPED AT U. S. ARMY PICATINNY ARSENAL. DOVER. N.J.
BY ROBERT E. BARNAS :
AND ROBERT I. ISAKOWER
OF MANAGEMENT INFORMATION SYSTEMS DIRECTORATE.
SCIENTIFIC AND ENGINEERING APPLICATIONS DIVISION.

CLYDE-TEK,STEPPED + GROOVED SHAFT,CYLINDRICAL COORD. R=4. DX=1. DEL-SQ=0. 6/1/77

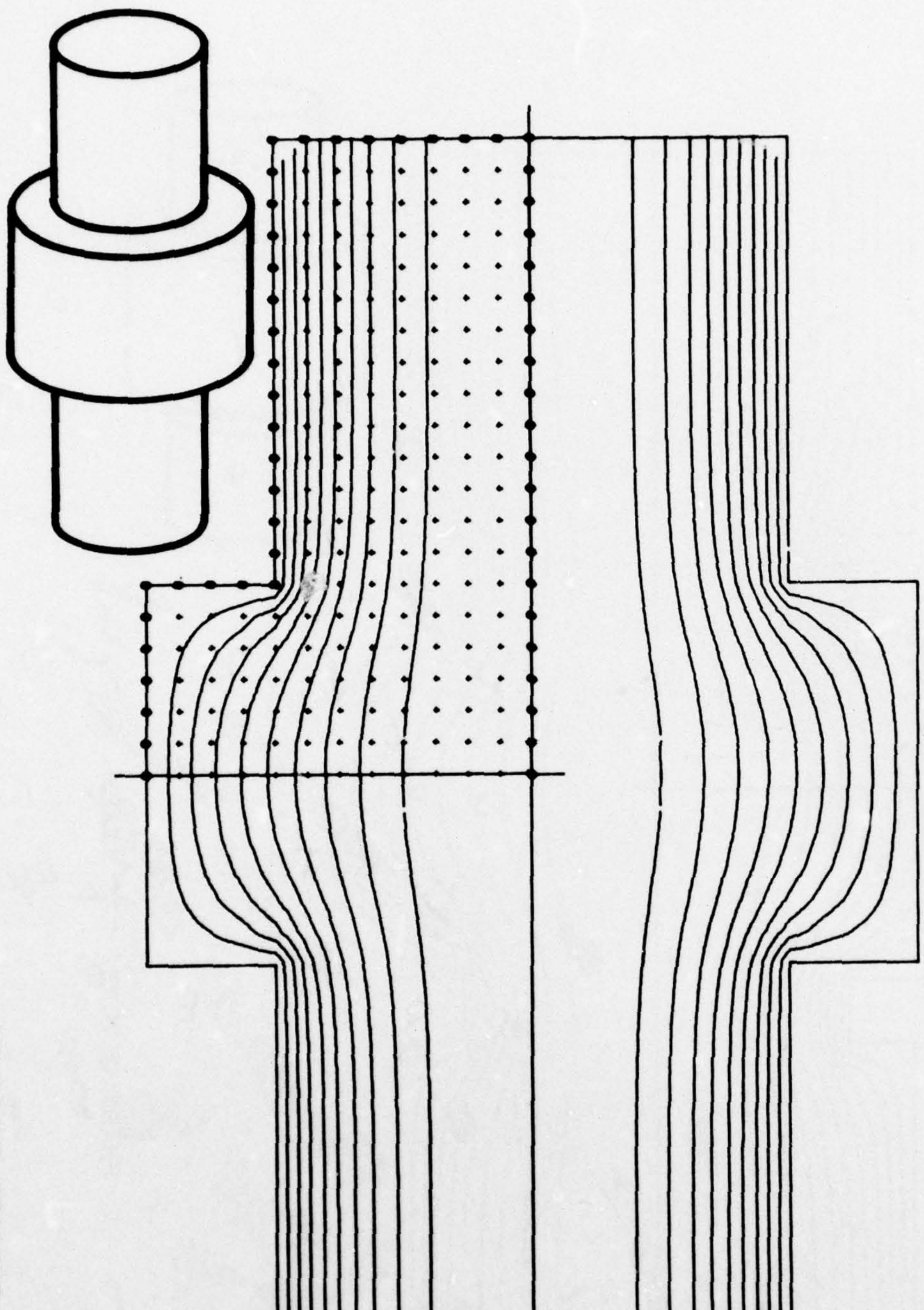
NUMBER OF NODE	X-COORDINATE	Y-COORDINATE	NODE VALUE
1	0.00000	1.00000	-6.4102635473
2	0.00000	2.00000	19.3662907480
3	0.00000	3.00000	150.2525879528
4	0.00000	4.00000	355.2327775154
5	0.00000	5.00000	621.4020932192
6	1.00000	1.00000	-7.9789544077
7	1.00000	2.00000	25.5599886057
8	1.00000	3.00000	197.1722634659
9	1.00000	4.00000	412.9787466822
10	1.00000	5.00000	661.9028810534
11	2.00000	1.00000	-12.7255597805
12	2.00000	2.00000	47.5437680220
13	2.00000	3.00000	393.6071096609
14	2.00000	4.00000	611.8810462895
15	2.00000	5.00000	789.3370603074
[illegible]	3.00000	1.00000	-19.1514007032
[illegible]	3.00000	2.00000	88.4830356827
[illegible]	4.00000	1.00000	-19.6385251910
[illegible]	4.00000	2.00000	89.9033259394
[illegible]	5.00000	1.00000	-14.4510370911
21	5.00000	2.00000	55.4976871592
22	5.00000	3.00000	478.5282967929
23	6.00000	1.00000	-10.4167795938
24	6.00000	2.00000	37.7446634087
25	6.00000	3.00000	330.8666564327
26	7.00000	1.00000	-8.3437495799
27	7.00000	2.00000	30.9936666567
28	7.00000	3.00000	288.3213338248
29	8.00000	1.00000	-7.4613853973
30	8.00000	2.00000	28.7512315266
31	8.00000	3.00000	275.9281788814
32	9.00000	1.00000	-7.1261762462
33	9.00000	2.00000	28.0866391746
34	9.00000	3.00000	272.2645344108

LISTING OF OUTPUT OF STRESS FUNCTION VALUES AT NODES IN FINITE DIFFERENCE GRID.

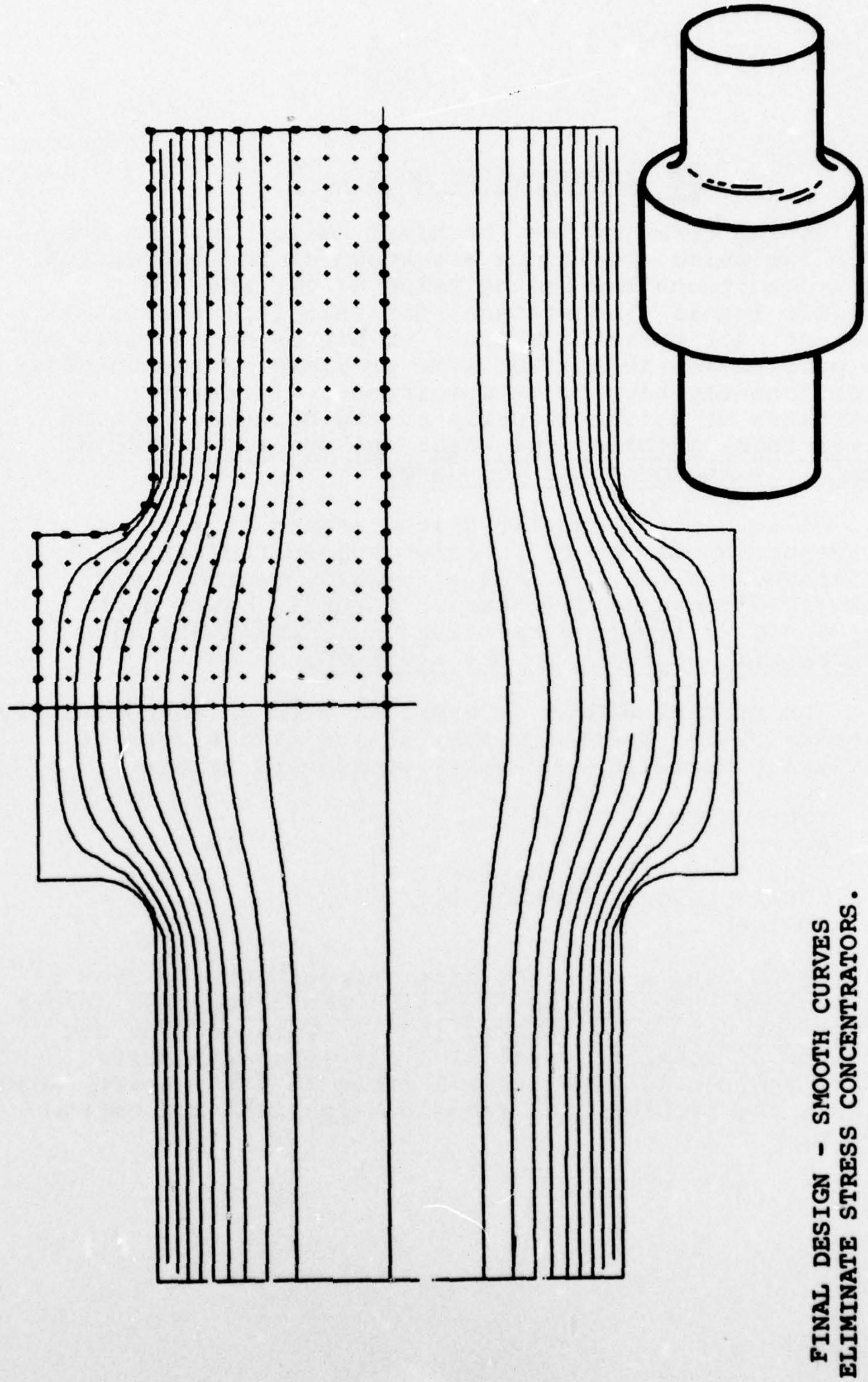
GOGOIGO //// END OF LIST ////



SHARP GROOVES ARE STRESS RAISERS.



ELIMINATION OF GROOVES IMPROVES
STRESS PATTERN.



FINAL DESIGN - SMOOTH CURVES
ELIMINATE STRESS CONCENTRATORS.

B. MATHEMATICAL MODEL

As the term implies, boundary value problems are those for which conditions are known at the boundaries. These conditions may be the value of the problem variable itself (temperature, for example), the normal gradient (or variable slope), or higher derivatives of the problem variable. For some problems, mixed boundary conditions may have to be specified: different conditions at different parts of the boundary. CLYDE solves those problems for which the problem variable, itself, is known at the boundary.

Given sets of equally spaced arguments and corresponding tables of function values the finite difference analyst may employ forward, central, and backward difference operators. CLYDE is based upon the central difference operators to approximate each differential operator in the equation.

The problem domain is overlaid with an appropriately selected grid. There are many shapes (and sizes) of overlaying cartesian and polar coordinate grids:

rectangular..
square..
equilateral - triangular..
equilangular - hexagonal..
oblique..

CLYDE uses a constant size (throughout the area of the problem) square grid for which the percentage errors are of the grid size squared (h^2). This grid or net consists of parallel vertical lines (spaced h units apart) and parallel horizontal lines (h units apart) which blanket the problem area from left-to-right and bottom-to-top.

The intersection of the grid lines with the boundaries of the domain are called boundary nodes. The intersections of the grid lines with each other within the problem domain are called inner domain nodes. It is at these inner domain nodes that the finite difference approximations are applied. The approximation of the partial differential equation with the proper finite difference operators replaces the PDE with a set of subsidiary linear algebraic equations - one at each inner domain node. For the practical application of the method, it must be capable of solving problems whose boundaries may be curved. In such cases, boundary nodes are not all exactly h units away from an inner node as is the case between adjacent inner nodes. The finite difference approximation (of the harmonic operator) at each inner node involves not only the variable value at that node and at the four surrounding nodes (above, below, left and right) but also the distance between these four surrounding nodes and the inner node - and at the boundaries these distances, quite likely, vary unpredictably. Compensation for the variation of these distances must be included in the finite difference solution. CLYDE represents the problem variable by a second degree polynomial in two variables, and employs a generalized irregular star in all directions for each inner node. In practice, one should not select such a coarse grid that more than (or even) two arms of the star are irregular (or less than h units in length). The generalized star permits (and automatically compensates for) a variation in length of any of the four arms radiating from a node. For no variation in any arm, the algorithm reduces exactly to the standard harmonic "computation stencil".

CONSIDER THE GENERAL EXPRESSION:

$$\nabla^2 f = A\frac{\partial^2 f}{\partial \eta^2} + B\frac{\partial^2 f}{\partial \xi^2} + \frac{C}{\lambda}\frac{\partial f}{\partial \lambda} = D \quad ..EQ\,(1)$$

IN THE η, ξ, λ COORDINATE SYSTEM,

WHERE A, B, C, D ARE ARBITRARY CONSTANTS.

WHEN C=O, $\nabla^2 f$ REDUCES TO A TWO COORDINATE SYSTEM, SAY IN X AND Y:

$$\nabla^2 f = A\frac{\partial^2 f}{\partial x^2} + B\frac{\partial^2 f}{\partial y^2} = D \quad ..EQ\,(2)$$

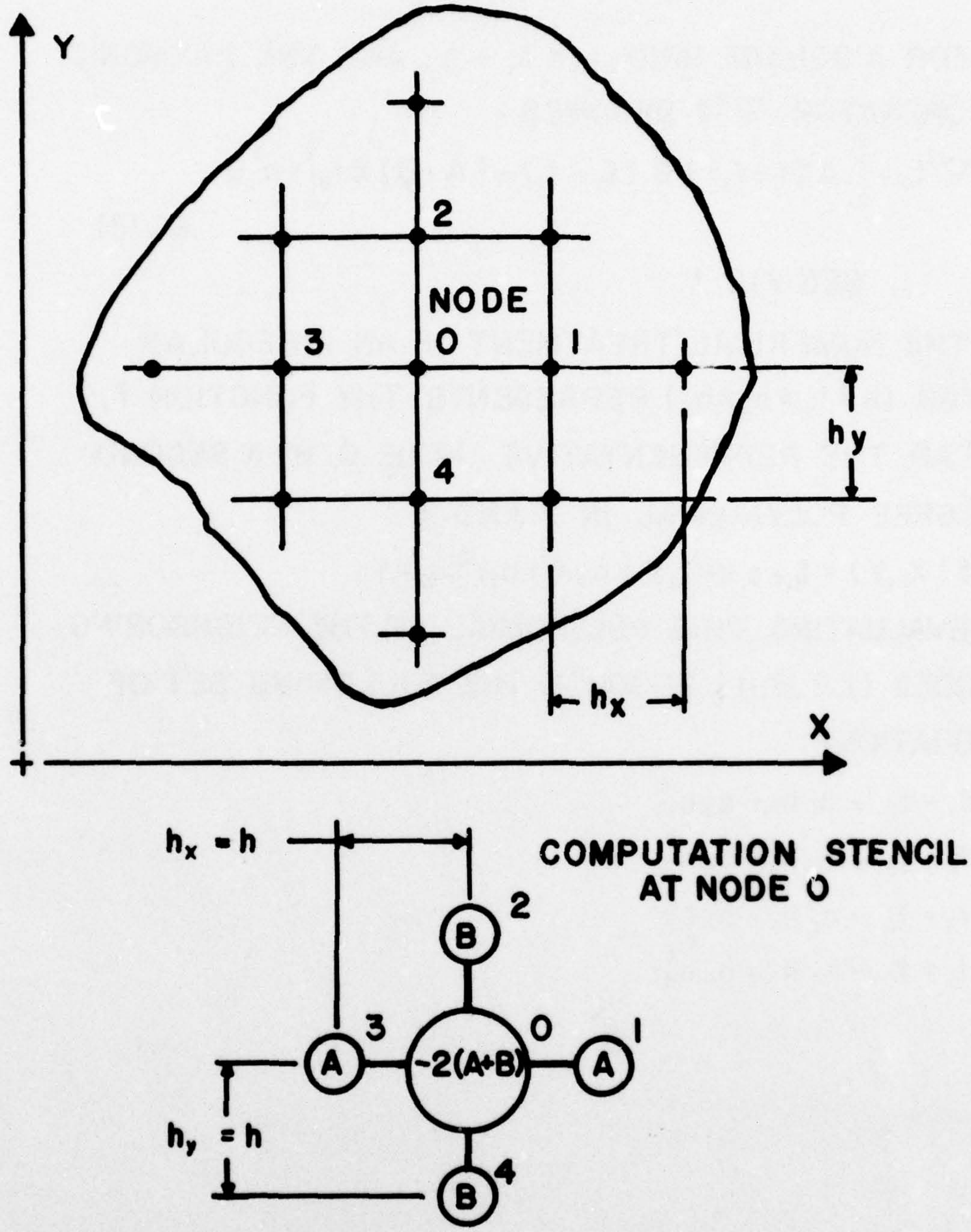
USING CENTRAL DIFFERENCES, THE FINITE DIFFERENCE APPROXIMATIONS TO THE PARTIAL DIFFERENTIAL OPERATORS, OF THE FUNCTION f, AT REPRESENTATIVE

NODE O ARE:

$$\frac{\partial f}{\partial x} = \frac{1}{2h_x}(f_1 - f_3), \quad \frac{\partial f}{\partial y} = \frac{1}{2h_y}(f_2 - f_4)$$

$$\frac{\partial^2 f}{\partial x^2} = \frac{1}{h_x^2}(f_1 - 2f_0 + f_3)$$

$$\frac{\partial^2 f}{\partial y^2} = \frac{1}{h_y^2}(f_2 - 2f_0 + f_4)$$



1. HARMONIC OPERATOR FOR SQUARE GRID

$$\nabla^2 f = A\frac{\partial^2 f}{\partial X^2} + B\frac{\partial^2 f}{\partial Y^2} = D$$

FOR A SQUARE GRID, $h_x = h_y = h$, AND THE HARMONIC OPERATOR $\nabla^2 f$ BECOMES:

$$h^2 \nabla^2 f_0 = \Big[A\,(f_1 + f_3) + B\,(f_2 + f_4) - (A+B)\,2 f_0 \Big] = h^2 D$$

..EQ (3)

SEE FIG. 1

THE NUMERICAL TREATMENT OF AN IRREGULAR STAR ($h_1 \neq h_2 \neq h_3 \neq h_4$) REPRESENTS THE FUNCTION f, NEAR THE REPRESENTATIVE NODE O, BY A SECOND DEGREE POLYNOMIAL IN X AND Y:

$$f(X, Y) = f_0 + a_1 X + a_2 Y + a_3 X^2 + a_4 Y^2 + a_5 XY$$

EVALUATING THIS POLYNOMIAL AT THE NEIGHBORING NODES (1, 2, 3, 4) PRODUCE THE FOLLOWING SET OF EQUATIONS:

$$f_1 = f_0 + a_1 h_1 + a_3 h_1^2$$

$$f_2 = f_0 + a_2 h_2 + a_4 h_2^2$$

$$f_3 = f_0 - a_1 h_3 + a_3 h_3^2$$

$$f_4 = f_0 - a_2 h_4 + a_4 h_4^2$$

WHICH ARE THEN SOLVED FOR a_3 AND a_4, WHICH ARE NECESSARY TO SATISFY THE HARMONIC OPERATOR $\nabla^2 f$, SINCE :

$$\frac{\partial f}{\partial x} = a_1 + 2a_3 X + a_5 Y, \quad \frac{\partial^2 f}{\partial x^2} = 2a_3$$

$$\frac{\partial f}{\partial Y} = a_2 + 2a_4 Y + a_5 X, \quad \frac{\partial^2 f}{\partial Y^2} = 2a_4$$

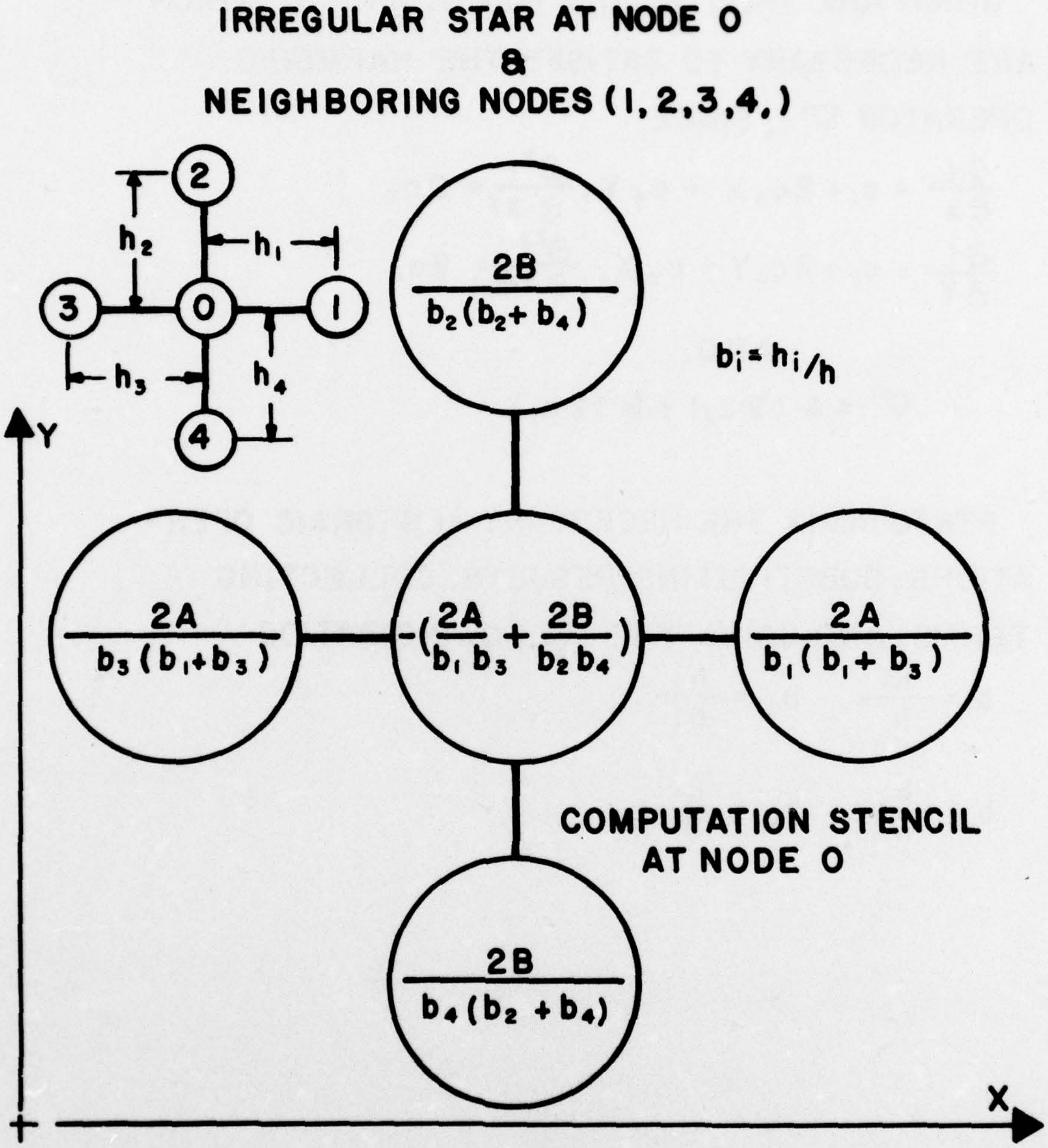
AND

$$\nabla^2 f = A(2a_3) + B(2a_4)$$

PERFORMING THE NECESSARY ALGEBRAIC OPERATIONS, SUBSTITUTING RESULTS, COLLECTING TERMS, AND USING THE FOLLOWING RATIOS :

$$b_1 = \frac{h_1}{h} \qquad b_2 = \frac{h_2}{h}$$

$$b_3 = \frac{h_3}{h} \qquad b_4 = \frac{h_4}{h}$$



2. HARMONIC OPERATOR FOR IRREGULAR GRID

$$\nabla^2 f = A\frac{\partial^2 f}{\partial X^2} + B\frac{\partial^2 f}{\partial Y^2} = D$$

THE HARMONIC OPERATOR BECOMES:

$$h^2\nabla^2 f_0 = \Big[\frac{2A}{b_1(b_1+b_3)} f_1 + \frac{2B}{b_2(b_2+b_4)} f_2 + $$

$$+ \frac{2A}{b_3(b_1+b_3)} f_3 + \frac{2B}{b_4(b_2+b_4)} f_4 + $$

$$- \left(\frac{2A}{b_1 b_2} + \frac{2B}{b_2 b_4}\right) f_0\Big] = h^2 D \quad ..\text{EQ (4)}$$

SEE FIG. 2

WHEN $C \neq 0$, $\nabla^2 f$ CAN BE APPLIED TO A (AXISYMMETRIC) CYLINDRICAL COORDINATE SYSTEM,

SAY IN R AND Z:

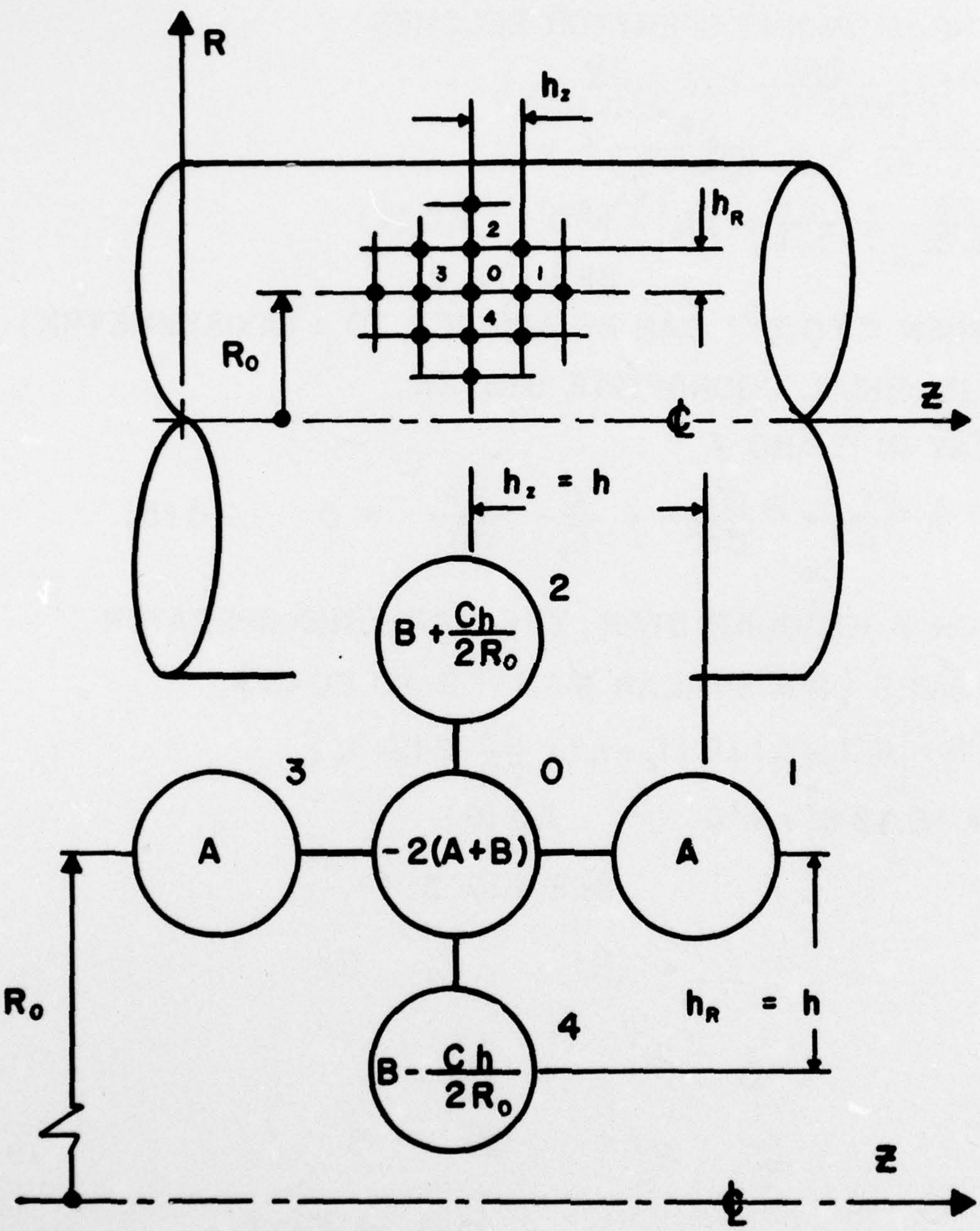
$$\nabla^2 f = A\frac{\partial^2 f}{\partial Z^2} + B\frac{\partial^2 f}{\partial R^2} + \frac{C}{R}\frac{\partial f}{\partial R} = D \quad ..\text{EQ (5)}$$

FOR A REGULAR STAR, THE HARMONIC OPERATOR BECOMES (IN A SIMILAR MANNER TO EQ (3)):

$$h^2\nabla^2 f_0 = \Big[A(f_1+f_3) + B(f_2+f_4) + \frac{Ch}{2R_0}(f_2 - f_4)$$

$$-(A+B)\,2 f_0\Big] = h^2 D \quad ..\text{EQ (6)}$$

SEE FIG. 3



3. HARMONIC OPERATOR FOR SQUARE GRID

$$\nabla^2 f = A \frac{\partial^2 f}{\partial Z^2} + B \frac{\partial^2 f}{\partial R^2} + \frac{C}{R} \frac{\partial f}{\partial R} = D$$

FOR AN IRREGULAR STAR ($h_1 \neq h_2 \neq h_3 \neq h_4$)

THE HARMONIC OPERATOR BECOMES (IN A MANNER SIMILAR TO EQ (4)):

$$h^2 \nabla^2 f_0 = \left[\frac{2A}{b_1(b_1+b_3)} f_1 + \frac{2B}{b_2(b_2+b_4)} f_2 + \right.$$

$$+ \frac{2A}{b_3(b_1+b_3)} f_3 + \frac{2B}{b_4(b_2+b_4)} f_4 +$$

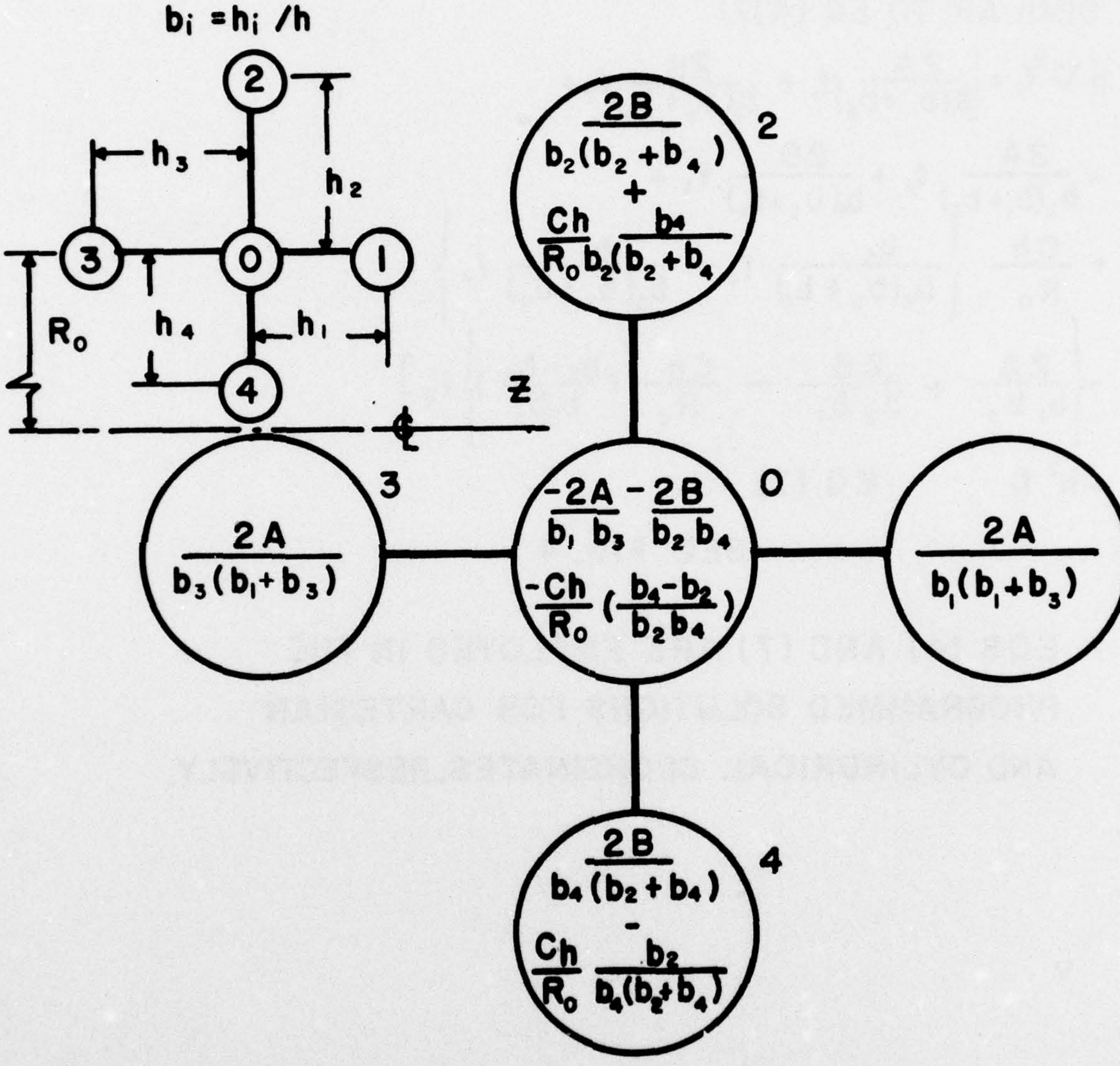
$$+ \frac{Ch}{R_0} \left\{ \frac{b_4}{b_2(b_2+b_4)} f_2 - \frac{b_2}{b_4(b_2+b_4)} f_4 \right\} +$$

$$\left. - \left\{ \frac{2A}{b_1 b_3} + \frac{2B}{b_2 b_4} - \frac{Ch}{R_0} \left(\frac{b_2 - b_4}{b_2 b_4} \right) \right\} f_0 \right]$$

$$= h^2 D \qquad .. \text{EQ } (7)$$

SEE FIG. 4

EQS (4) AND (7) ARE EMPLOYED IN THE PROGRAMMED SOLUTIONS FOR CARTESIAN AND CYLINDRICAL COORDINATES, RESPECTIVELY.



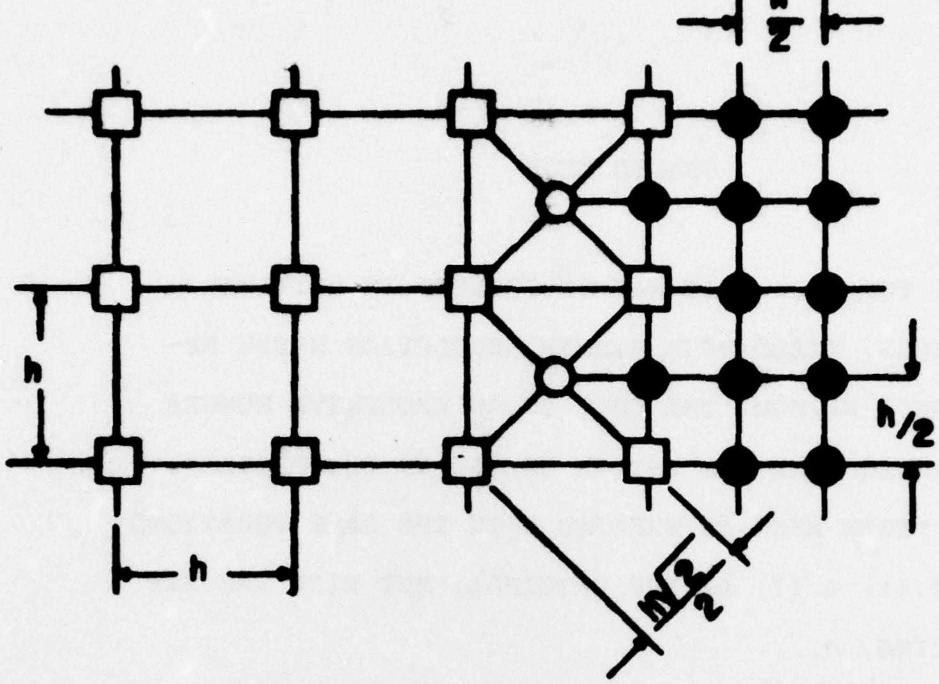
4. HARMONIC OPERATOR FOR IRREGULAR GRID

$$\nabla^2 f = A\frac{\partial^2 f}{\partial Z^2} + B\frac{\partial^2 f}{\partial R^2} + \frac{C}{R}\frac{\partial f}{\partial R} = D$$

GRADED MESH

THE MESH SIZE MAY BE REDUCED IN CRITICAL REGIONS, YIELDING A HIGHER RESOLUTION WHERE REQUIRED, WITHOUT THE COST OF AN EXCESSIVE NUMBER OF NODES OVER THE ENTIRE DOMAIN OF THE PROBLEM. THE FINER MESH IS TREATED WITH THE SAME EQUATIONS (EQS.(4) & (7) AS THE ORIGINAL, BUT WITH THE NEW SPACING, h.

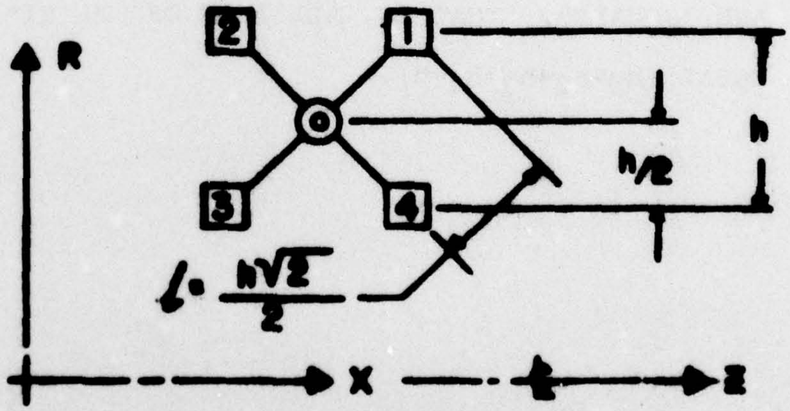
BETWEEN THE ORIGINAL (COARSE) AND NEW (FINER) MESH, HOWEVER, THERE EXISTS AN INTERMEDIATE MESH OR NET THAT REQUIRES SPECIAL TREATMENT. THIS INTERMEDIATE MESH WILL NOW BE CONSIDERED FOR BOTH CARTESIAN (EQ (4)) AND CYLINDRICAL (EQ (7)) COORDINATE SYSTEMS. NOTE THAT INTERMEDIATE MESH GRIDS ARE "SQUARE". THAT IS, ALL ARMS OF THE STAR ARE EQUAL ($h_1=h_2=h_3=h_4=h$).



□ ORIGINAL MESH (OR NET) NODE

● FINER MESH NODE

○ INTERMEDIATE MESH NODE



USING ABOVE NOTATION FOR INTERMEDIATE NODES & USING "AVERAGING" DIFFERENCES:

$$\ell^2 \nabla^2 f_{X,Y} = A\frac{\partial^2 f}{\partial X^2} + B\frac{\partial^2 f}{\partial Y^2} = D\ell^2$$

BECOMES

$$\left(\frac{A+B}{2}\right)\left[f_1 + f_2 + f_3 + f_4 - 4f_0\right] = D\ell^2$$

$$= D\frac{h^2}{2} \qquad ..\text{EQ}(8)$$

$$\ell^2 \nabla^2 f_{R,Z} = A\frac{\partial^2 f}{\partial Z^2} + B\frac{\partial^2 f}{\partial R^2} + \frac{C}{\partial R} \frac{\partial f}{\partial R^2} = D\ell^2$$

BECOMES

$$\left(\frac{A+B}{2} + \frac{C\ell}{4R}\right)(f_1 + f_2) + \left(\frac{A+B}{2} - \frac{C\ell}{4R}\right)(f_3 + f_4)$$

$$-\left(\frac{A+B}{2}\right) 4f_0 = D\ell^2 = \frac{Dh^2}{2} \qquad ..\text{EQ}(9)$$

WHERE $\frac{C\ell}{4R}$ IS $\frac{Ch}{8R}\sqrt{2}$

C. THINGS TO COME

FLAT PLATE ANALYSIS

The deflection (w) of a thin plate loaded normal to its plane is described by the fourth order partial differential equation:

$$\frac{\partial^4 W}{\partial X^4} + 2\frac{\partial^4 W}{\partial X^2 \partial Y^2} + \frac{\partial^4 W}{\partial Y^4} = g(x,y)$$

Unfortunately, because of the many plate configurations possible, a generalized finite difference operator for an irregular boundary value problem perversely resists formulation. It is possible, however, to replace the fourth order equation with two equations of the second order, since:

$$\nabla^4 f = \nabla^2(\nabla^2 f)$$

The two equations (see eq. 12a,b) are of the same kind as that obtained for a uniformly stretched and laterally loaded membrane and are solved, not simultaneously, but sequentially. The input or forcing function of the first equation is the lateral loading g(x,y), and the solution variable is the bending moment vector M at each node. This bending moment vector is the "loading" input to the second equation which, when solved, yields the deflection of the plate at each node.

This solution had already been incorporated into the earlier refresh graphics version (CLYDE-274) for simply supported plates (M=0,w=0 on the boundaries), yielding excellent results. Batch and storage tube graphics versions are planned, tailored to solve plate problems with a variety of edge restraints (simply supported, built-in or "fixed", free edges, etc..).

THE BIHARMONIC OPERATOR

$$\nabla^4 W = \frac{\partial^4 W}{\partial x^4} + 2\frac{\partial^4 W}{\partial x^2 \partial Y^2} + \frac{\partial^4 W}{\partial Y^4} = \frac{q}{D} \quad \cdot\cdot \text{EQ (10)}$$

CAN BE REPLACED BY TWO SECOND ORDER EQUATIONS

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial Y^2}\right)\left(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial Y^2}\right) = \frac{q}{D} \quad \cdot\cdot \text{EQ (11)}$$

SINCE

$$M_x = -D\left(\frac{\partial^2 W}{\partial x^2} + \mu\frac{\partial^2 W}{\partial Y^2}\right) \quad \text{AND}$$

$$M_y = -D\left(\frac{\partial^2 W}{\partial Y^2} + \mu\frac{\partial^2 W}{\partial x^2}\right)$$

$$M_x + M_y = -D(1+\mu)\left(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial Y^2}\right)$$

INTRODUCING A NEW NOTATION

$$M = \frac{M_x + M_y}{1+\mu} = -D\left(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial Y^2}\right)$$

EQ (11) MAY BE REPRESENTED BY

$$\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial Y^2} = -q \quad \cdot\cdot\cdot \text{EQ (12a)}$$

$$\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial Y^2} = -\frac{M}{D} \quad \cdot\cdot \text{EQ (12b)}$$

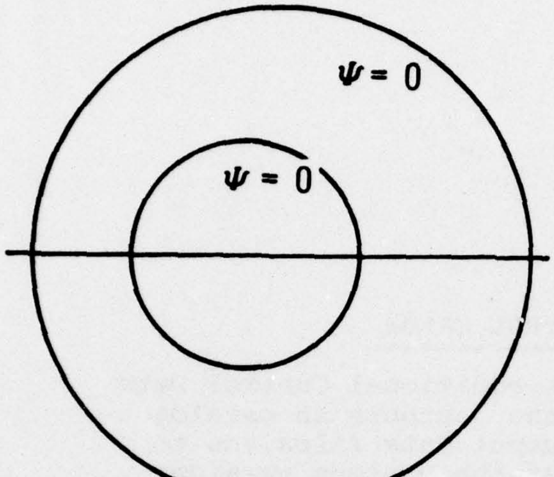
TORSION OF HOLLOWED SHAFT

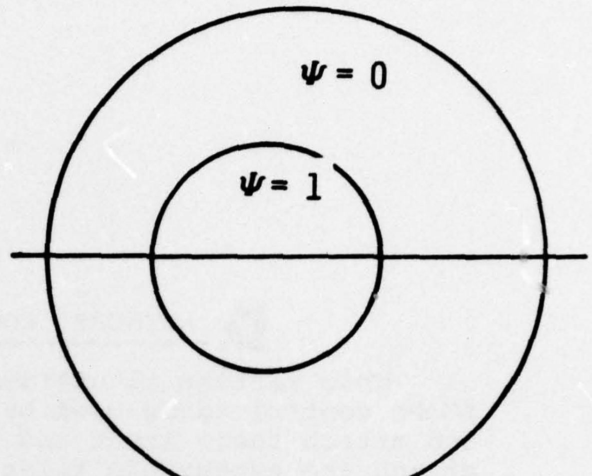
This would appear to be a simple matter of solving the governing PDE over a multiply-connected boundary, were it not for the uncertainty concerning boundary conditions. The actual value of the problem variable at the boundary was not important in the torsion application, only the difference in the problem variable at various points mattered. The problem variable at the boundary could be assumed to have any value, as long as there was only one boundary. With two (or more) boundaries the solution calls for a different approach.

The stress function is obtained as the superposition[1] of two solutions, one of which is adjusted by a factor (k). This is the planned programmed solution to shafts with a hole. The hole may be of any shape, size, and location. The two solutions, to be combined, are shown at the right: equations and boundary conditions. This capability already exists in CLYDE. What will be added is the solution for k and then the final superposition of results. Once the contour integrals are taken around the inner boundary of the area A_B, the only unknown, k, may be readily obtained. The contour integral need not be evaluated around the entire boundary, but may be taken around any contour that encloses that boundary, and includes none other (for example, see shaded area A_B).

1) Reference (5), pgs 8,11,23

READ INSTRUCTIONS

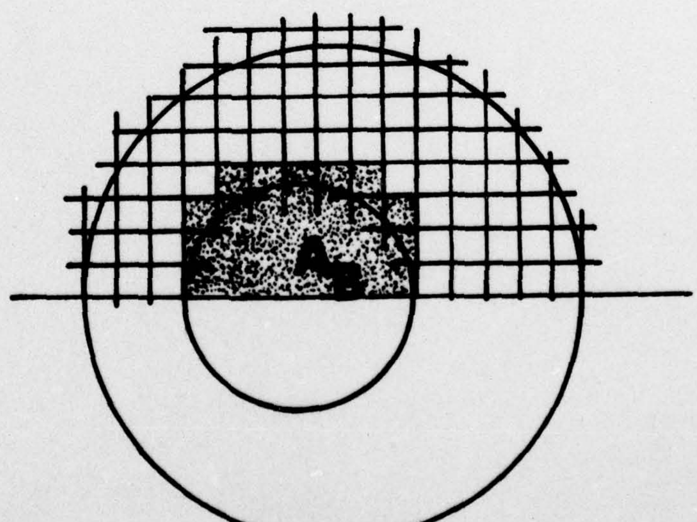




$\nabla^2 \psi_0 = -2$ $\qquad\qquad$ $\nabla^2 \psi_1 = 0$

$$\psi = \psi_0 + k\,\psi_1$$

$$-2A_B = \oint \frac{\partial \psi_0}{\partial \nu}\, ds + k \oint \frac{\partial \psi_1}{\partial \nu}\, ds$$



D. AUTHORS' CONTROL CARDS

This section illustrates additional Control Data SCOPE control cards used by the authors to catalog and attach their input and output data files and to attach the executable files of the various versions of the CLYDE family. This is for illustrative purposes only. Users are enjoined not to blindly copy these control cards, but to develop their own file names. Users may, and in fact must, exactly duplicate and use the ATTACH commands ending in "ID=MISDSEAD" in order to use the CLYDE programs. They should not reproduce the authors' COMMENT cards or control commands containing "ID=ISAKOWER" or "ID=BARNAS". Violators will be shot.

PROGRAM CLYDE-TEK CONTROL CARDS

PROGRAMMER | DATE | PUNCHING INSTRUCTIONS | GRAPHIC | PUNCH | PAGE OF | CARD ELECTRO NUMBER

FORTRAN STATEMENT | IDENTIFICATION SEQUENCE

```
7/8/9 ← (multiple 7,8,9 punch in column 1)
[illegible]. ← ([illegible] card)
COMMENT.([illegible]), ISAKOWER ← (See Digital Systems Handbook)

PURGE,DATAP,CLYDE2TEK,ID=ISAKOWER.
PURGE,CC.
EXIT.
REQUEST,DATA,[illegible].
COPYCR,INPUT,DATA.
CATALOG,DATA,CLYDE2TEK,ID=ISAKOWER.
7/8/9 ← (multiple 7,8,9 punch in column 1)
{CLYDE-TEK INPUT DATA CARDS}

6/7/8/9 ← (multiple 6,7,8,9 punch in column 1)
```

CONTROL CARD PACKAGE TO READ IN PUNCH CARD INPUT FOR CLYDE-TEK.

AUTHOR'S INITILIZATION OF TEKTRONIX 4014 TERMINAL TO RUN CLYDE-TEK AT 300 BAUD.

1. Turn terminal (switch 1 foot from floor) and hard copier on.

2. Put LOCAL/LINE switch to LOCAL.

3. Let terminal and copier warm up.

4. Settings:

   CODE EXPANDER to OFF
   CLEAR WRITE to OFF
   A&B toggle switch to B
   ROTARY BAUD switch to 300 (rear of terminal)
   ASCII/BCD switch to ASCII (" " ")
   Phone SELECT switch CW to OPT

5. Hit RESET PAGE key.

6. Hit SHIFT and RESET PAGE keys together.

7. Hit SHIFT, CTRL, and P keys together.

8. Hit RETURN key (R).

9. Put LOCAL/LINE switch to LINE.

10. At GRAY phone, depress TALK button.

11. Dial 361-6036 to connect to CDC 6500.

12. When computer answers with constant tone, depress DATA button and hang up.

13. LOGIN when requested by system.

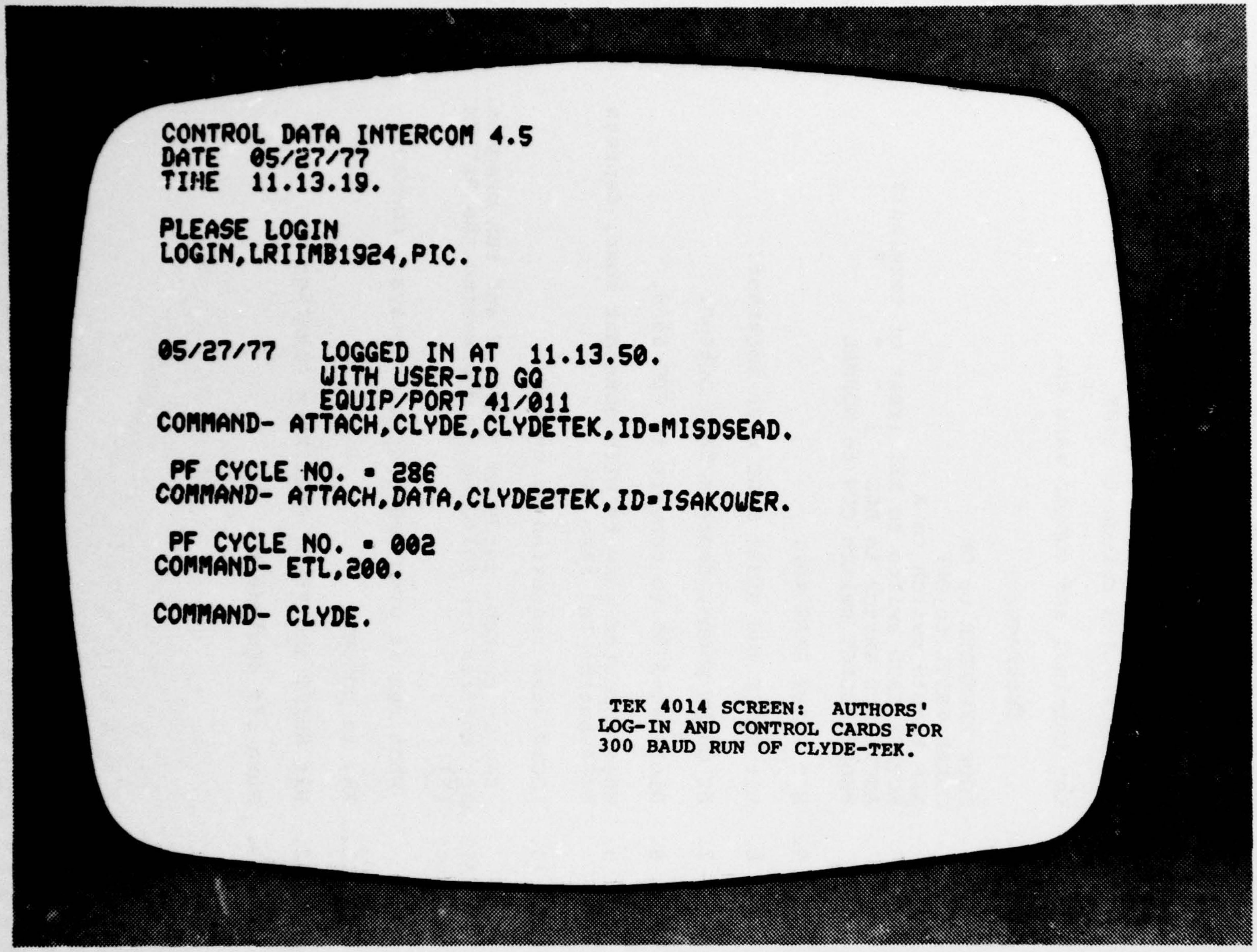
Key in control cards as required and run program. All user keyboard entries are followed by depressing the RETURN key (this is symbolized in instructions by R).

When program run is over and system displays: COMMAND-

14. Key in LOGOUT.

15. Hit SHIFT and RESET PAGE keys together.

16. Turn off equipment.



TEK 4014 SCREEN: AUTHORS' LOG-IN AND CONTROL CARDS FOR 300 BAUD RUN OF CLYDE-TEK.

AUTHOR'S INITIALIZATION OF TEKTRONIX 4014 TERMINAL TO RUN CLYDE-TEK at 4800 BAUD.

1. Turn terminal (switch 1 foot from floor) and hard copier on.

2. Put LOCAL/LINE switch to LINE.

3. Let terminal and copier warm up.

4. Settings:

   CODE EXPANDER to ON
   CLEAR WRITE to OFF
   A&B toggle switch to A
   ROTARY BAUD switch to EXT (rear of terminal)
   ASCII/BCD switch to BCD (" " ")
   PHONE SELECT switch CCW to NORMAL

5. Hit RESET PAGE key.

6. Hit SHIFT and RESET PAGE keys together.

7. At GREEN phone, depress TALK button.

8. Dial 361-3785 to convert to CDC 6500.

9. When computer answers with constant tone, depress DATA button and hang up.

10. LOGIN when requested by system.

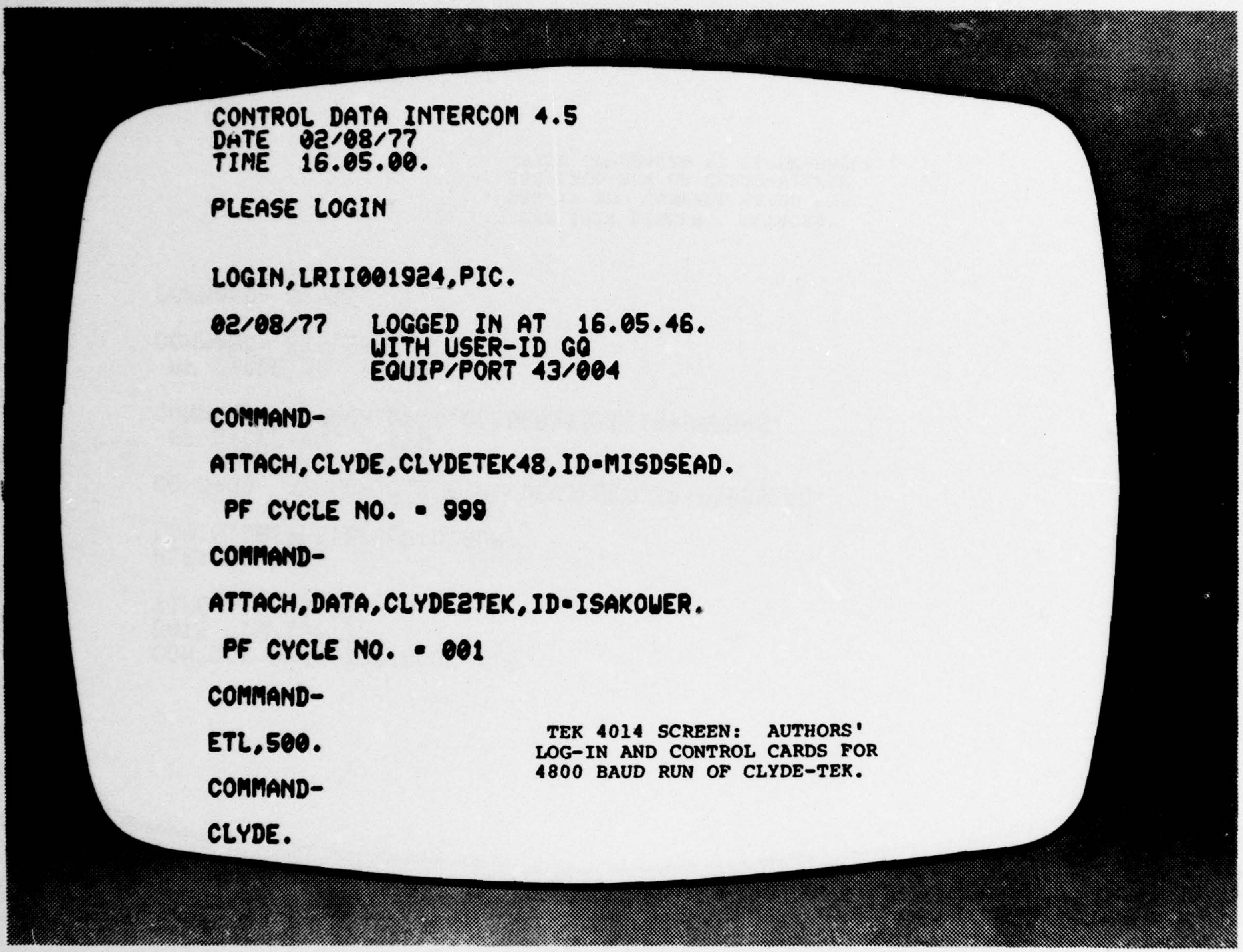
Key in control cards as required and run program. All user entries are followed by depressing the RETURN key (R).

When run is over and system displays: COMMAND -

11. Key in LOGOUT.

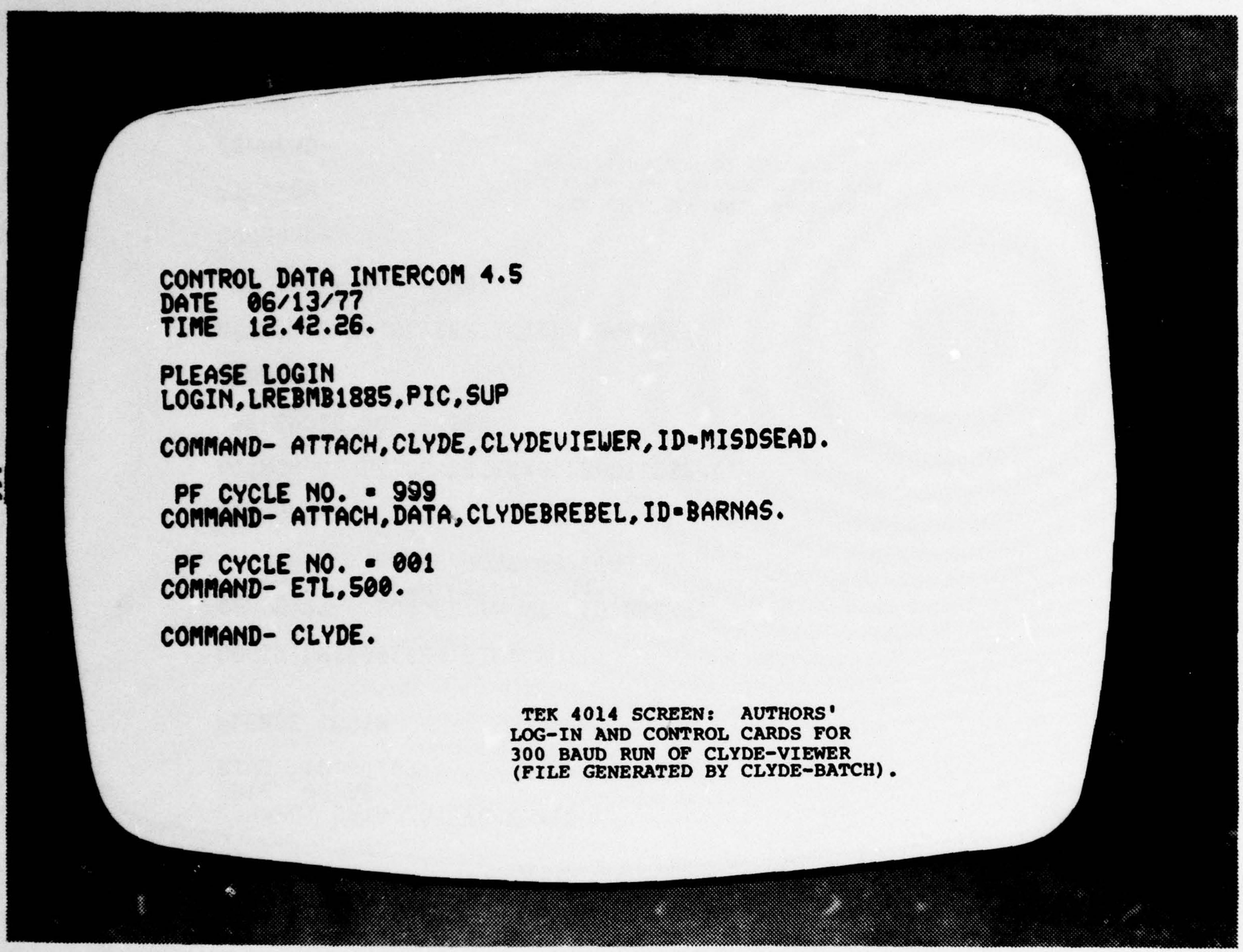
12. Hit SHIFT and RESET PAGE keys together.

13. Turn off equipment.

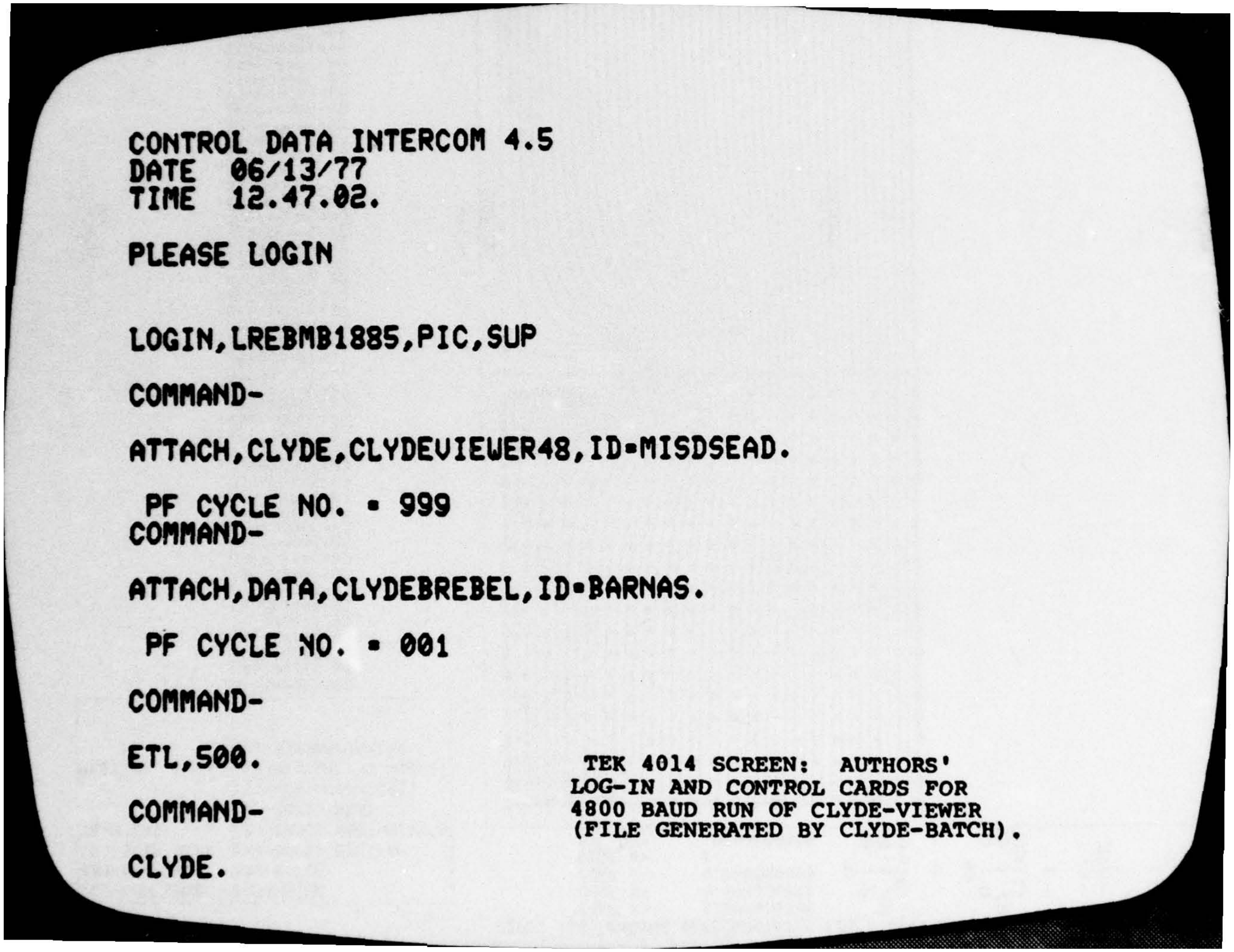


```
CONTROL DATA INTERCOM 4.5
DATE  02/08/77
TIME  16.05.00.

PLEASE LOGIN

LOGIN,LRII001924,PIC.

02/08/77   LOGGED IN AT  16.05.46.
           WITH USER-ID GQ
           EQUIP/PORT 43/004

COMMAND-

ATTACH,CLYDE,CLYDETEK48,ID=MISDSEAD.

 PF CYCLE NO. = 999

COMMAND-

ATTACH,DATA,CLYDE2TEK,ID=ISAKOWER.

 PF CYCLE NO. = 001

COMMAND-

ETL,500.

COMMAND-

CLYDE.
```

TEK 4014 SCREEN: AUTHORS' LOG-IN AND CONTROL CARDS FOR 4800 BAUD RUN OF CLYDE-TEK.

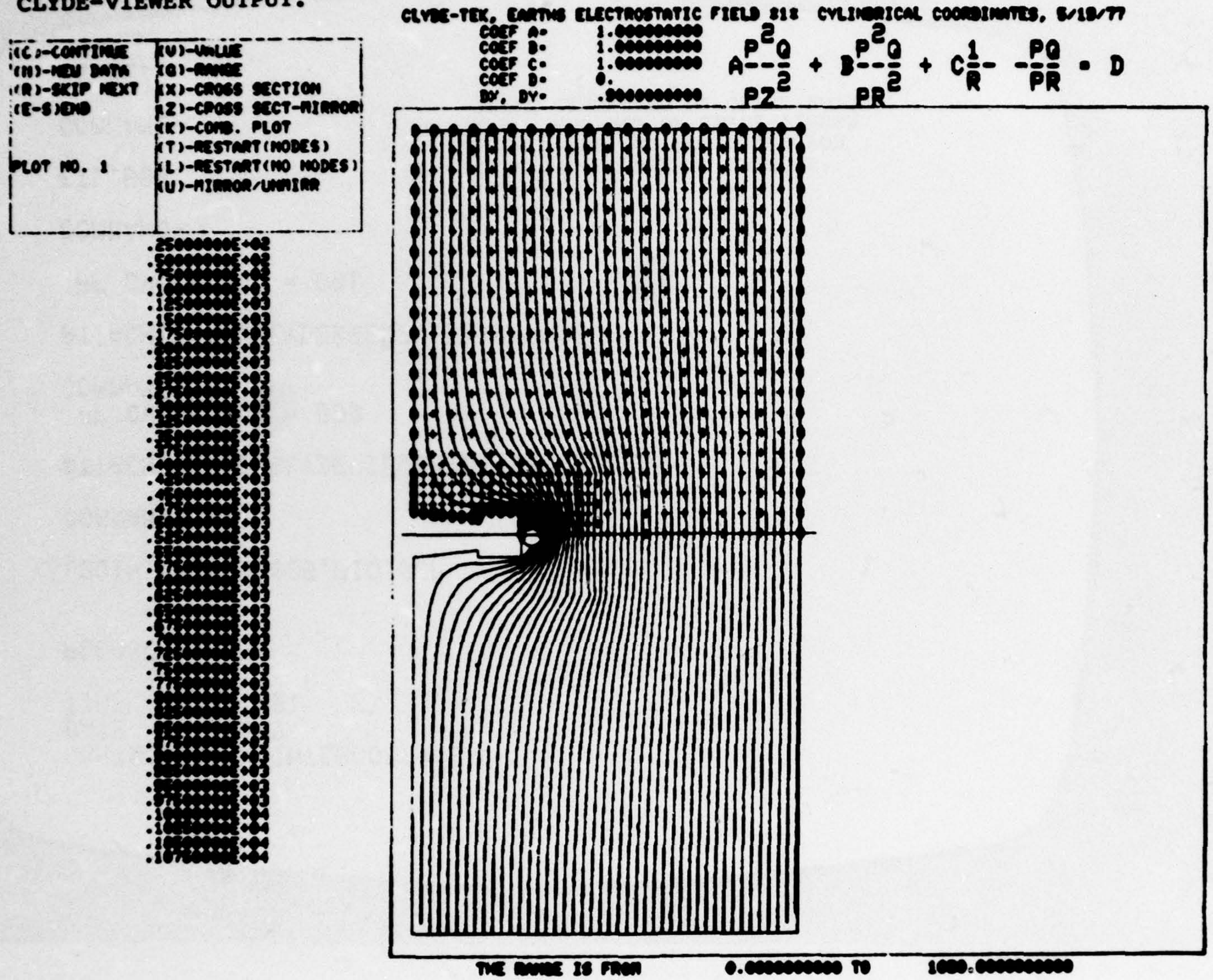


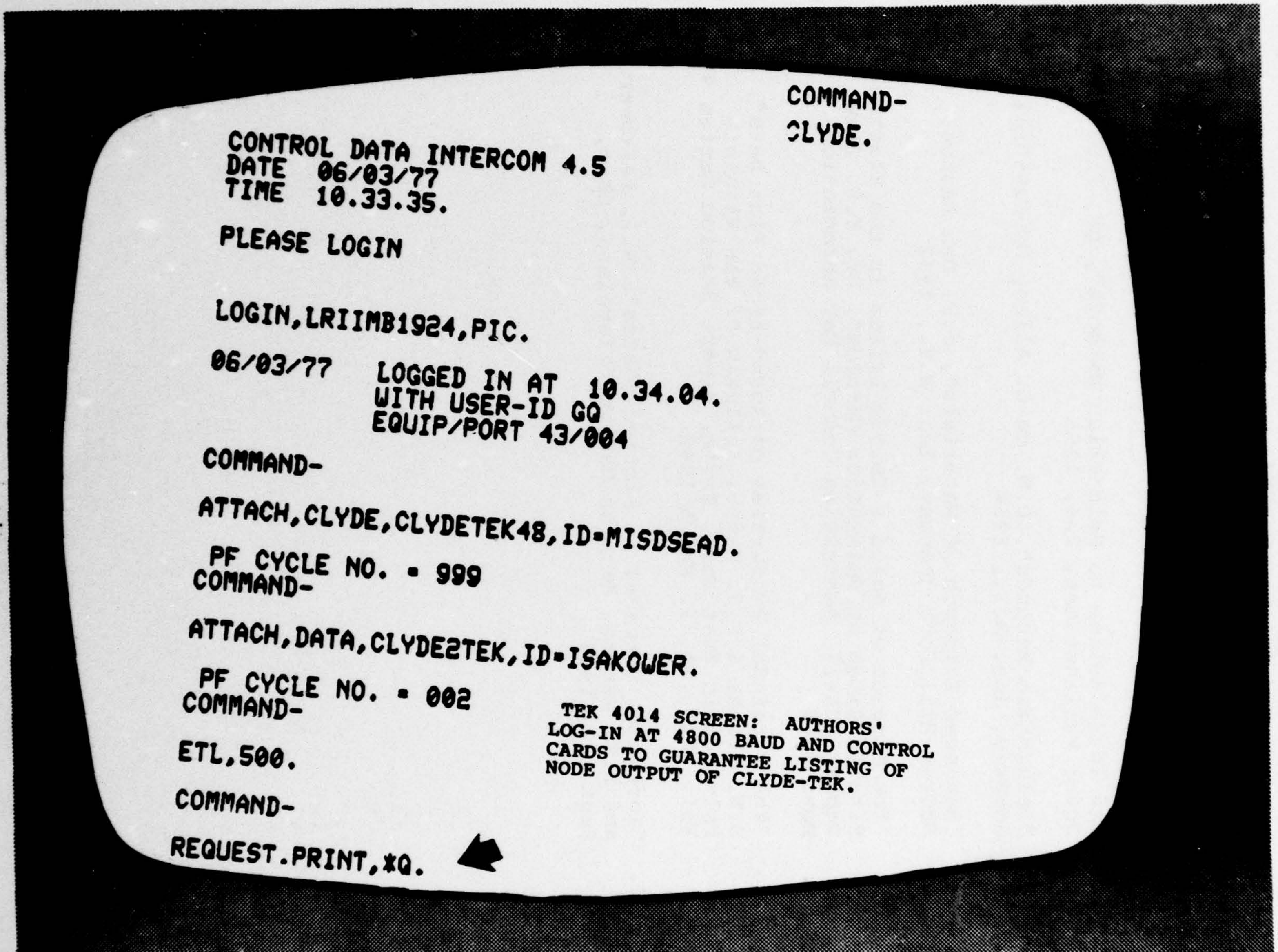
TEK 4014 SCREEN: AUTHORS' LOG-IN AND CONTROL CARDS FOR 300 BAUD RUN OF CLYDE-VIEWER (FILE GENERATED BY CLYDE-BATCH).



TEK 4014 SCREEN: AUTHORS' LOG-IN AND CONTROL CARDS FOR 4800 BAUD RUN OF CLYDE-VIEWER (FILE GENERATED BY CLYDE-BATCH).

TEK 4014 SCREEN:
CLYDE-VIEWER OUTPUT.





TEK 4014 SCREEN: AUTHORS' LOG-IN AT 4800 BAUD AND CONTROL CARDS TO GUARANTEE LISTING OF NODE OUTPUT OF CLYDE-TEK.

E. REFERENCES

1. "CLYDE" MISD Information Report 73-1, R.I. Isakower and R.E. Barnas, Picatinny Arsenal, Dover, N.J. 07801, January 1973

2. "An Introduction to Relaxation Methods", Dr. F.S. Shaw, Dover Publications, Inc. 1953

3. "Relaxation Methods", D.N. de G. Allen, McGraw-Hill Book Company, Inc. N.Y., 1954

4. "Advanced Strength of Materials", J.P. Den Hartog, McGraw-Hill Book Company, Inc. N.Y., 1952

5. "The Torsion of Solid & Hollow Prisms in the Elastic & Plastic Range by Relaxation Methods", Dr. F.S. Shaw, Report ACA-11, Australian Council For Aeronautics, Nov. 1944

6. "The Torsional Properties of Round-Edged Flat Bars", D.H. Pletta & F.J. Mayer, Bulletin of the Virginia Polytechnic Institute, Eng'g. Exper. Station Series #50, Vol. XXXV, No. 7, March 1942

7. "Torsional Stresses in Slotted Shafts", R.I. Isakower and R.E. Barnas, Machine Design, Cleveland, Ohio, Sept. 22, 1977

F. THE BOOK OF CLYDE

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4. TITLE (and Subtitle) THE BOOK OF CLYDE (WITH A TORQUE-ING CHAPTER)		5. TYPE OF REPORT & PERIOD COVERED COMPUTER PROGRAM USERS MANUAL (FINAL)
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) ROBERT I. ISAKOWER ROBERT E. BARNAS		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS MANAGEMENT INFORMATION SYSTEMS DIRECTORATE		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. ARRADCOM DOVER, N.J. 07801		12. REPORT DATE OCTOBER 1977
		13. NUMBER OF PAGES 176
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

PARTIAL	CLYDE	LAPLACE	TORSION	POTENTIAL
DIFFERENTIAL	FINITE	POISSON	GRAPHICS	GRID
EQUATIONS	DIFFERENCES	MEMBRANE	ARRADCOM	COMPUTER
PDE	HARMONIC	SOAP-FILM	ELECTROSTATIC	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

CLYDE is a computer language for your differential equations. It provides numerical solutions to an important class of second order elliptic partial differential equations (Laplace and Poisson) which appear in almost every branch of applied mechanics: governing the solutions to design problems in heat conduction, stress concentration, and potential fields (electric, magnetic, electrostatic, gravitation, irrotational fluid flow, etc..).

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20 (continued

There are three versions of CLYDE. This document describes the capabilities of the CDC 6000/TEKTRONIX 4014 storage tube graphics version (CLYDE-TEK) and the batch version (CLYDE-B) and also serves as a preliminary user's manual. An earlier version (CLYDE-274), written for the CDC 6500/1700/274 refresh graphics facility, is described in MISD Information Report 73-1, January 1973, and includes the extension of the solution to the fourth order stress analysis equation for flat plates. All CLYDE versions were written for CDC 6000 host computers under the SCOPE operating system with overlay structures. Two applications covered in detail in this document are steady state heat conduction and the membrane or soap film analogy of torsion of bars and shafts.